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Modelling Roundabout Capacities

by

Yok Hoe Yap

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

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MODELLING ROUNDABOUT CAPACITIES

Yok Hoe Yap

There has been extensive research and development into the capacity of modern offside priority roundabouts since the 1970's. Despite this, there remains a major gap in existing knowledge with regards to the factors and variables which affect roundabout entry capacity. This is reflected in the differences and inconsistencies in inputs and methodologies between existing state-of-the-art models.

Evaluations with recent data collected from 35 roundabout entry lanes in the field have shown that this limits the accuracy of state-of-the-art models, particularly in their ability to explain site-to-site variation in entry capacities. New empirical models have thus been developed for lane capacity using regression, and benchmarking against neural networks showed that they performed well with the shortlisted explanatory variables. These regression models were based on exponential-in-Q_c and linear-in-Q_c forms, and outperformed existing state-of-the-art models.

In the new models, entry-exit separation distance and exiting flows on the same arm were found to be more useful predictor variables (when used in conjunction with other variables) compared to others used in more-established models (e.g. entry radius and entry angle). To investigate the effects of separation distance and exiting flows through microscopic simulation, stochasticity in separation distances was modelled through a novel approach in Vissim involving multiple exit connectors. This was significant as the variability of separation distances had not been explored before, whether through analytical or simulation approaches.

The separation distance was found to have a piecewise linear relationship with capacity, while exiting flows had a linear positive relationship which becomes negative as the inhibitory effect increased at low separation distances. The two main mechanisms explaining these effects of exiting flows were the inhibitory mechanism (caused by drivers unable to distinguish between circulating and exiting vehicles), and changes in circulating headways. A revised empirical model incorporating this piecewise relationship performed as well as the exponential-in-Q_c and linear-in-Q_c models, suggesting that the impacts of exiting flows were modelled reasonably well. By improving our understanding of the impacts of these two variables on capacity, this is an important step towards the improved modelling of roundabout entry capacity.

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DECLARATION OF AUTHORSHIP

I, YOK HOE YAP,

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

MODELLING ROUNDABOUT CAPACITIES

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:
    - YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (2013) An International Review of Roundabout Capacity Modelling, Transport Reviews, 33 (5), pp. 593-616.
    - YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (in press) Models of Roundabout Lane Capacity, Journal of Transportation Engineering, American Society of Civil Engineers.

Signed:...

Date:..

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Chapter 1: Introduction

This introductory chapter will briefly describe the current state of roundabout use, and the role of capacity modelling in the design process. It then set outs the rationale for this research into roundabout capacity modelling, and outlines the corresponding aims and objectives.

1.1 Roundabouts

Modern roundabouts are a major type of junction on the road network, where entering vehicles give-way to vehicles circulating one-way around a central island. As shown in Figure 1-1, there are various types of roundabouts in use, differing in terms of size, geometry and overall capacity. Of these, turbo roundabouts have become increasingly popular in continental Europe, particularly in Holland and Germany (de Baan, 2012; Brilon, 2011; Fortuijn, 2009a). This study will however focus on normal roundabouts, as the other types may be regarded as derivatives arising from space, safety, capacity or other constraints, but they all operate on the same fundamental principle.

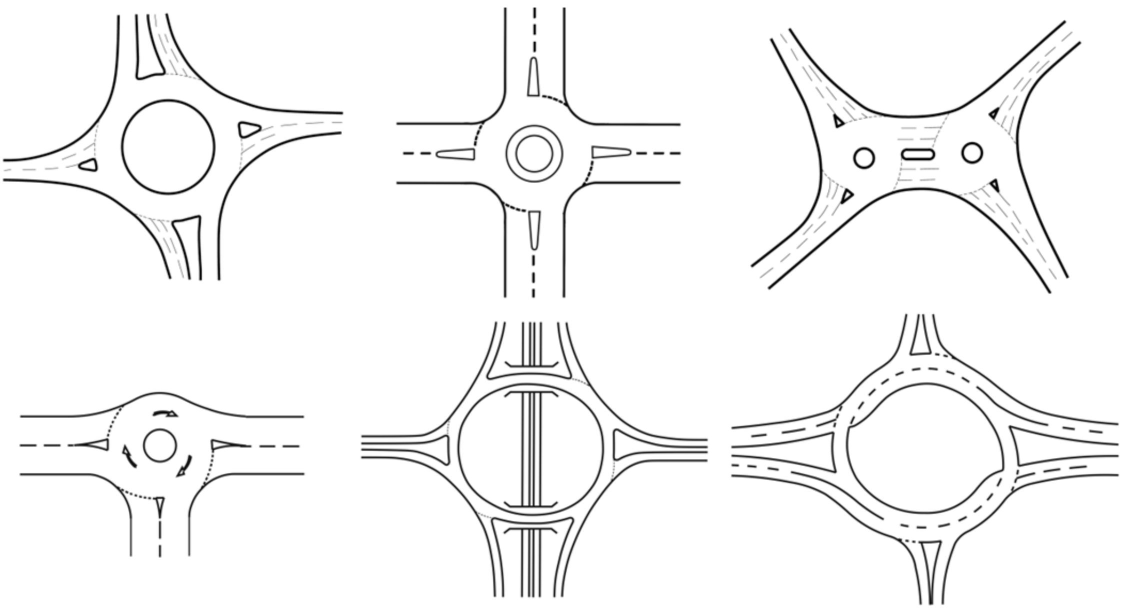


Figure 1-1 Clockwise from top left: Normal roundabout, compact roundabout, double roundabout, turbo-roundabout, grade-separated roundabout, mini-roundabout (adapted from Department for Transport, 2007b; Department for Transport, 2007c; Department of Transport, 1993)

Roundabouts have been shown to have a superior vehicle safety record compared to other forms of at-grade junctions on the road network (Department for Transport, 2007b; Transportation Research Board, 2007) and this is also reflected by their lower accident costs (Department for Transport, 2004). The severity of crashes is reduced as perpendicular crossing conflicts are avoided and approaching vehicles are forced to slow down through deflection (Transportation Research Board, 2010b, p.5-15).

1.2 Roundabout traffic performance, design and the role of capacity analysis

Delays on roundabouts are a key measure of their operational performance, and comprise geometric delays and queuing delays. The former mainly arise from vehicles slowing down to safely negotiate the junction in free-flow conditions (McDonald *et al.*, 1984), but the latter result from a combination of random arrivals and oversaturated conditions and are typically estimated using time-dependent queuing models such as those of Kimber and Hollis (1979) or Akçelik and Troutbeck (1991, cited in Akçelik *et al.*, 1998). The ratio of demand flow to capacity (RFC) determines queue lengths and queuing delays in these models, and thus entry capacity is a key variable as it essentially reflects the queue discharge rate. Other methods to determine queues and delays include those based on equivalent blocked/unblocked periods in gap acceptance for back-of-queue estimation in SIDRA (Akçelik and Chung, 1994), those based on gap acceptance variables (Flannery *et al.*, 2005) or those in microscopic simulation models; however, as a rule, greater capacity leads to smaller queues and delays.

It is thus important to understand what factors and variables influence capacity, and how it may be calculated. Capacity analysis uses appropriate models – such as those reviewed later in section 2.2 – to check if the requisite operational performance in terms of capacity, queues and delays can be achieved with the given geometric layout of the roundabout. It typically forms the core of any assessment of proposed and existing roundabouts.

The geometric design of a roundabout must typically conform to statutory standards and guidelines such as TD 16/07 (Department for Transport, 2007b), the AASHTO Geometric Design Policy (AASHTO, 2011), FHWA Roundabout Guide

2010 (Transportation Research Board, 2010b) or Austroads design guides (Austroads, 2009) which specify criteria for geometry, visibility and cross-sectional features to satisfy safety and operational requirements. The geometric design must also satisfy spatial limitations which can be particularly onerous in densely-developed areas, as well as accommodate the swept path of design vehicles.

Given the complexity of the roundabout form and its relationship with capacity, the typical design process for a roundabout usually involves alternating between geometric design and capacity analysis until an optimal solution in terms of performance and cost is achieved. State-of-the-art software can considerably speed up this process (Savoy Computing Services Ltd, 2012); an early example was ROBOSIGN (Irani *et al.*, 1993) but current solutions such as AutoTrack Junctions-ARCADY (Savoy Computing Services Ltd, 2010; TRL Software, 2012) and TORUS-SIDRA (Transoft Solutions Inc, 2012; Akcelik & Associates Pty Ltd, 2013) include automated vehicle swept path analysis and allow near-simultaneous geometric design and capacity analysis.

Good roundabout design prioritises operational performance and safety for all its users, including pedestrian and cycle traffic. However, the success of any design is usually determined by its traffic performance, and thus accurate modelling of its capacity is essential for better and more economic roundabout designs.

1.3 Problem definition, Aims and Objectives

Capacity models for modern roundabouts (as opposed to older traffic circles or ‘conventional’ roundabouts which do not operate on the offside priority principle) have been developed since the 1970’s, typically through various empirical or semi-empirical approaches and with varying degrees of theoretical input from gap acceptance principles or microscopic simulation. The age of several of these models raises questions over their accuracy given the gradual evolution in roundabout design (exemplified by the introduction of compact or turbo roundabouts), vehicle characteristics and possibly driver behaviour. Furthermore, the international major capacity models were necessarily based on the driver and vehicle populations in the originating countries, which then raises questions over their transferability to other countries.

The aim of this study is thus to improve on the current knowledge in the field of roundabout capacity modelling, so that capacity predictions can be improved for better prediction of traffic performance for new roundabouts.

The specific objectives are to improve the understanding of:

- the state-of-the-art in roundabout capacity modelling
- the limitations of existing roundabout capacity modelling approaches
- whether the predominant capacity models are still applicable in the present-day context given the passage of time and potential changes in roundabout designs, vehicle performance and driver behaviour
- the factors and variables which significantly affect entry capacity but have not been included in existing models.

For practical reasons, the focus will be on the U.K. roundabouts, for which the empirical LR942 model was established over three decades ago. However, the basic principles of roundabout operation and design are similar worldwide (Kennedy, 2007), so the transferability of this study's findings to other countries will also be considered in this study.

1.4 Report structure

In line with the above aim and objectives, the rest of this thesis is structured as follows.

Chapter 2 reviews the state-of-the-art in roundabout capacity modelling, outlining issues and limitations with current methodologies. The bulk of this chapter has been published as a paper in the Transport Reviews journal.

Chapter 3 discusses the collection of new capacity data for analysis necessitated by the conclusions of the review. It will discuss why an empirical approach is preferred, the characteristics of the proposed sample, and the limitations arising from the actual sample used. It also presents a small study comparing different methods of capacity data measurement, to address one of the limitations of empirical modelling.

Chapter 4 describes the application of the new data to the assessment of current methodologies, as well as the use of statistical regression and neural network modelling to assess the impact of variables and factors. It also identifies issues requiring further investigation, including the identification of new significant explanatory variables. The bulk of the work presented in Chapters 3 and 4 has been published as a paper in the Journal of Transportation Engineering.

Chapter 5 sets out the modelling methodology used to investigate the impact of two of the variables identified from the empirical study (separation distance and exit flow), including the use of a novel approach to model the stochasticity of separation distances.

Chapter 6 discusses the possible mechanisms for the impacts, and develops a revised empirical model for capacity which takes into account the hypothesised relationships between separation distance, exiting flows and capacity. The bulk of the work presented in Chapters 5 and 6 was presented as a paper in the Universities' Transport Study Group 2015 Annual Conference and thence submitted to the UTSG special issue of the Transportation Planning and Technology journal.

Chapter 7 presents the conclusions drawn from the work in this thesis, and discusses potential avenues for further research.

Chapter 2: Review of roundabout capacity and state-of-the-art modelling

This chapter will provide an overview of roundabout capacity concepts, before critically discussing the state-of-the-art in roundabout capacity modelling, including issues and limitations with existing modelling methodologies and their implications. The bulk of this chapter has undergone the peer review process and has been published as a journal paper: YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (2013) An International Review of Roundabout Capacity Modelling, Transport Reviews, 33 (5), pp. 593-616 available online: http://dx.doi.org/10.1080/01441647.2013.830160

2.1 Roundabout capacity

Capacity in the context of traffic engineering is defined as the "maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions" (Transportation Research Board, 2010a). The capacity of a roundabout entry can thus be defined as the "maximum inflow when the demand flow is large enough to cause steady queuing in the approach" (Kimber, 1980), which reflects the queue discharge rate.

This flow is averaged over the applicable analysis time interval to account for inherent short-term (i.e. minute-by-minute or vehicle-by-vehicle) variability resulting from the gap acceptance process. Although Troutbeck (1985; 1984) was of the opinion that the capacity should be based on an upper-bound envelope to observed entry flow data points, most roundabout capacity research (including that which will be presented in this report) use a mean value from saturated conditions (Transportation Research Board, 2007; Brilon, 2005; Akçelik *et al.*, 1998; Kimber, 1985) as this is more likely to repeatable and achievable with typical analysis time periods.

With the offside-priority rule, the entry capacity varies with the prevailing circulating flow across the entry as a result of the gap acceptance process. Entry capacity also depends on geometry as, for example, a wider multi-lane entry enables more vehicles to enter the same available gap, while bypass lanes increase capacity for traffic turning towards the first arm downstream (Mauro and Guerrieri, 2013; Tollazzi *et al.*, 2011). Capacity has also been found to be affected by environmental factors including rain and darkness (Tenekeci *et al.*, 2010), as well as other traffic factors aside from circulating flow, such as origin-destination demand patterns (Akçelik, 2004; Hagring, 2000a). Pedestrian crossings and exit blocking also reduce entry capacity, either by interrupting demand flows at the entry or causing queues inside the circulatory carriageway (Marlow and Maycock, 1982). The capacity of flared multi-lane entries also depends on the length of the additional lane and lane utilisation.

Entry capacity can be modelled by lane or by approach, where for a multilane entry, the approach or arm capacity is the sum of the individual lane capacities after allowing for any effects of flaring. The ratio of demand flow to capacity (RFC) is used for capacity analysis and design in deterministic models, where a ratio of over 1 indicates that demand flows are exceeding the capacity. The inherent variability of traffic flows and queues mean that an optimal RFC value of 0.85 is often chosen for design, as higher values may result in excessive queuing over more time periods, while lower values indicate that the design may be less economically justifiable (Department of Transport, 1981).

A roundabout typically has three or more arms, so the circulating flow across an entry depends on the junction turning movements and the entry flows and capacities of the other arms. The entry capacity value for an arm thus changes when any of the other flows change, so iterative methods are used to determine the final entry capacities for all the arms (Hollis, 1979; Akcelik & Associates Pty Ltd, 2013). If all the entry flows are uniformly increased using a common multiplier to maintain the same turning movement patterns, the roundabout can be defined to have reached its practical capacity when its most critical approach reaches the maximum specified RFC (Allsop, 1998; Wong, 1996); in the case of a multi-lane entry, it is the RFC of the critical lane which is used instead of the whole approach (Bie *et al.*, 2010). Dixit (2012), however, defined the capacity of roundabout as the maximum total outflow based on a macroscopic fundamental diagram relating average circulating flows and outflows to the traffic density on the roundabout. Performance measures based on delay-based level-of-service are also used to assess the capacity of the whole roundabout (Transportation Research Board, 2010a; Valdez *et al.*, 2011). However, given that roundabouts usually operate on offside priority with no exit restrictions, the system capacity will clearly depend on the entry capacity at each arm, so entry capacity will form the focus of this research.

2.1.1 Roundabout entry flows and link capacity

With the offside priority rule, the capacity of a roundabout entry lane can be considered as the flow (originating from the immediate queue at the entry) which is limited by the yield control mechanism at the entry, rather than by the ability of the upstream approach or link to supply the demand flow.

This distinction is important for capacity measurement, as the flow constrained by the upstream link is limited by link characteristics such as lane widths, lateral clearance, on-street parking, upstream junctions or pedestrian crossings, gradients or other geometric and traffic factors (Tenekeci *et al.*, 2014; Transportation Research Board, 2010a; The Institution of Highways and Transportation, 1997). These could result in link capacities becoming less than roundabout entry capacities, particularly with very low circulating flows and large demand flows. The flow approaching the roundabout may be restricted by congested flow conditions reflected in the fundamental diagram of traffic flow; although flow breakdown may initially be triggered by the capacity bottleneck of the roundabout entry (relative to the link's original capacity), the subsequent maximum entry flows could more likely reflect the reduced congested link capacity rather than that limited by the gap acceptance process at the entry.

Furthermore, pedestrian crossings, signals and high demand flows on the downstream link could reduce maximum flows at roundabouts by interrupting flows and causing queues to block-back and limit exit capacity. However, these phenomena depend on the conditions in the surrounding links, and thus modelling their effects will necessarily require more information on the links and nearby junctions, and alternative modelling approaches (Wu and Liu, 2011).

It is not clear to what extent field measurements of roundabout capacity flows or headway parameters in existing roundabout studies took into account the influence of link capacity flows described above. Given that they have typically been based on significantly congested roundabout entries in urban areas or on major routes, it is possible that congestion on the upstream links could have resulted in underestimated (and possibly more variable) roundabout entry capacity at lower circulating flows, and could perhaps be reflected in larger follow-on headways than expected.

2.1.2 Flaring and entry capacity

The use of flared approaches improves entry capacity by increasing the number of vehicles at the give-way line which can enter a given gap in the circulating flow. However, the maximum total entry flow may be limited by the capacity of the narrower section at the start of the flare as well as the storage capacity of the flared section; this is because some lanes may be unoccupied some or all of the time (i.e. entry starvation) depending on the length of the flare, lane queue lengths and turning movement patterns (Figure 2-1). In this case, the capacity of the approach could be considered as the sum of that of individual constituent lanes after allowing for entry starvation and other effects arising from flaring.

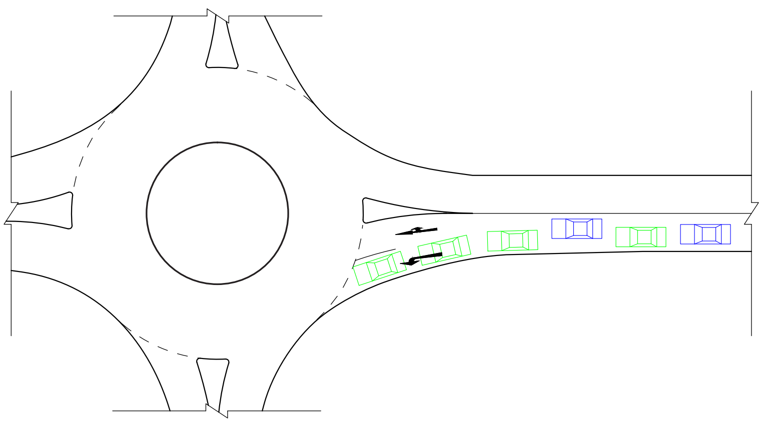


Figure 2-1 Starvation of offside lane in flared entry, due to queued left-turning traffic shown in green.

Although flaring increases the overall arm capacity, it can also reduce the observed flows in individual lanes across the give-way line. As shown in Figure 2-2, this is due to queued vehicles changing lanes and leaving gaps in the queue which do not close up before arriving at the give-way line (resulting in 'lost time' in the follow-on headways); this queue-splitting effect may be worse at low circulating flows when the queue is discharging at a higher speed and also at shorter flares with balanced lane choice proportions.

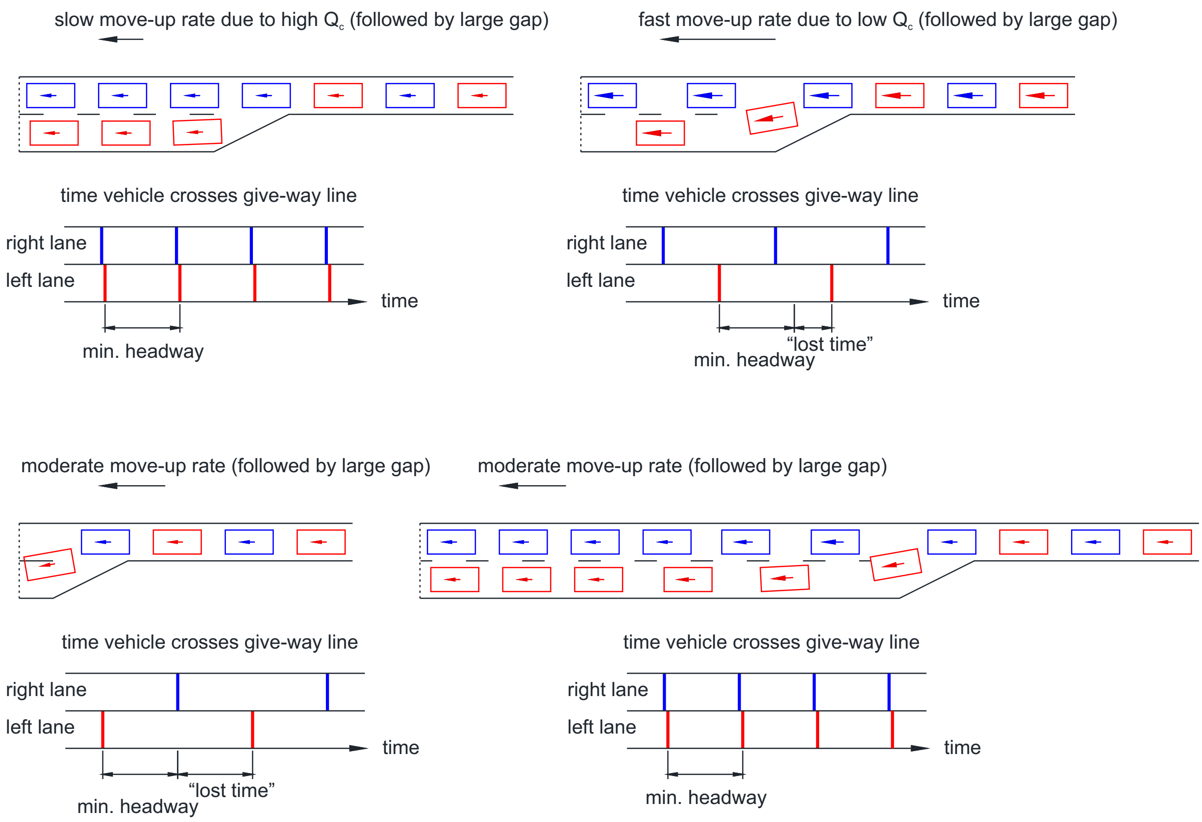


Figure 2-2 Illustration of the effects of flaring on lane entry headways, with differences in conflicting flow Q_c (top) and flare lengths (above).

Several models based on theoretical probabilistic or simulation approaches have been developed specifically to estimate the effects of flaring on entry capacity for unsignalised junctions or roundabouts (Burtenshaw, 2012; Wu, 2006; Wu, 1999; Akçelik, 1997). In contrast, the LR942 (Kimber, 1980) and RR142 (Semmens, 1988) capacity models directly calculate the arm capacity based on flare geometry, although they may not be suitable for scenarios with highly unbalanced lane use (Chard, 1997).

Given the additional complexities and data requirements involved in modelling the effects of flaring, this study will limit its scope to entry lane capacity as defined by the maximum entry flow rate across the give-way line for lanes unaffected by flaring. This is applicable to unflared entries or lanes in flared entries where the demand is unaffected by the splitting of queues. The effect of flaring on arm capacity, queues and delays would then be determined through suitable add-on models such as the Entry Lane Simulation of ARCADY / Junctions 8 (Burtenshaw, 2012).

2.2 Review of state-of-the-art in roundabout capacity modelling

With the conceptual definitions of roundabout entry capacity set out above, there is then a need to understand the state-of-the-art in how roundabout entry capacity has been modelled.

2.2.1 Entry capacity modelling

Given its reliance on gap acceptance, roundabout capacity can be considered as a function of geometry and demand flows, as well as driver and vehicle characteristics. A large number of factors, variables and mechanisms have previously been hypothesised to influence the gap acceptance process and capacity. However, practical limitations in research data collection, experimental design and sampling – partly arising from the inherent variability of queues, flows, vehicles and driver behaviour (Teply *et al.*, 1997; Kimber, 1989; Troutbeck, 1989; Kimber and Daly, 1986; Kimber, 1980) – has left room for the development of several competing schools of thought in roundabout capacity modelling. Several viable capacity models worldwide have thus been developed, which can be classified by their primary methodologies into the following categories:

- Empirical models based on relationships between geometry and actual measured capacity
- Gap acceptance models based on understanding driver behaviour
- Microscopic simulation models based on modelling of vehicle kinematics and interactions.

2.2.2 Empirical capacity models

Of the three underlying methodologies for roundabout capacity modelling, empirical capacity models based on the calibration of relationships between geometry and actual measured capacity are the longest established form. Empirical regression models are created through statistical multivariate regression analyses to fit mathematical relationships between measured entry capacity (Q_e), circulating flows (Q_c) and other independent variables which significantly affect entry capacity. The relationship between Q_e and Q_c is usually assumed to be linear ($Q_e=\alpha-\beta Q_c$) or exponential ($Q_e=\alpha e^{-\beta Q_c}$). Entry capacity can be directly measured from observed entry flows during continuous queuing at the entry, which are typically recorded with the corresponding circulating flows over time intervals of 0.5, 1 or more minutes.

2.2.2.1 LR942 linear regression model

The LR942 model is widely-acknowledged to be the best example of fully-empirical roundabout capacity models, being the standard model in the U.K. (Department of Transport, 1981) and the core of the ARCADY / Junctions 8 (TRL Software, 2012) and RODEL (Rodel Software Ltd, 2012) capacity analysis software. It was derived from extensive field data collected in the 1970's, with over 11,000 minutes of capacity data covering over 86 public roundabout entries (Kimber, 1980).

The model is approach-based (rather than lane-based) and thus explicitly includes the effects of flaring, albeit with the assumption of relatively balanced lane usage with insignificant entry starvation. Given the lack of evidence for non-linearity from the data, the model is linear in the relationship between entry capacity (Q_e) and circulating flow (Q_c), both in pcu/h units:

$$Q_e = k(F - f_c Q_c)$$

where k was a function of entry radius and entry angle, while F and f_c were functions of flare geometry (i.e. half-width of the approaching road, entry width and effective flare length), with external inscribed circle diameter at the entry also being included in f_c.

The sensitivity of the LR942 model to these six geometric parameters can be attributed to its inclusion of results from track experiments where geometry and traffic conditions could be controlled, enabling detailed investigations of the impact of flare geometry on capacity (Kimber and Semmens, 1977); an extensive review in 1995 found that the core principles and the form of the relationship remained valid (Barnard *et al.*, 1995).

2.2.2.2 French Girabase model

There were several early linear regression models in France, including those by SETRA (Louah, 1988) and CETUR (Alphand *et al.*, 1991). CETE Mediterranean's model was based on the Harders gap acceptance model (Brilon, 1988) for multilane roundabouts but had limited validation (Louah, 1992). Following on from these, the Girabase model by CETE West, was based on data obtained from 507 saturated intervals of 5 to 10 minutes on 45 roundabouts (Guichet, 1997). Although it was based on the Siegloch gap acceptance model, it is classified here as an empirical regression model as the critical gap and follow-on headways were selected to calibrate the model, rather than being obtained from the field measurements (Louah, 1992). Through statistical analysis, the entry capacity (pcu/h) is (Guichet, 1997):

$$Q_e = \left[\frac{3600}{t_f}\left(\frac{W_e}{3.5}\right)^{0.8}\right] e^{-C_b Q_d}$$

Where t_f is the follow-on headway, W_e was the entry width, C_b is an adjustment factor between urban and rural areas and the Q_d is a function of circulating flow, exiting flow leaving at the same arm, and geometric parameters.

2.2.2.3 Neural networks

Statistical regression approaches are constrained by the need for *a priori* knowledge on the form of the relationships between independent and dependent variables. These relationships can be difficult to identify from exploratory data analyses due to the large scatter of measured at-capacity entry flows in public roundabouts (Transportation Research Board, 2007, p.49).

Artificial neural networks have thus been used as an alternative for complex and highly non-linear relationships (Karlaftis and Vlahogianni, 2011; Dougherty, 1995). They are mathematical models based on an architecture consisting of one or more hidden layers with several artificial neural cells with activation functions. Using a large set of input-output data, they are trained through learning algorithms to optimise weights and biases. Provided that it is suitably-structured and not been over-trained, a neural network can be used to produce good predictions from new input data. An example developed by Özuysal *et al.* (2009) produced better estimated capacities from a sample of Turkish roundabout data compared to those of gap acceptance and regression models. However, the effect of individual inputs on capacity cannot be easily interpreted from the optimised weights and biases, which could limit the use of neural networks for design purposes as the application to any design types not included in the original training dataset can be unpredictable.

2.2.3 Limitations of empirical modelling

Empirical models map the relationship between input parameters and capacity, but do not necessarily prove causality nor provide a complete theoretical understanding of those relationships. Although this does not obviate their use as predictive tools, it is important to understand the underlying principles as there may be atypical scenarios where engineering judgement is needed to assess the validity of the predicted capacities. This is a particular issue with roundabout design, which may need to conform to unusual site constraints with different arm sizes or orientations.

The parameters included in a model should adequately describe all the key features of a roundabout which might affect capacity, as the omission of any significant parameter could result in poorer predictive performance. However, bearing in mind that data collection costs typically increase with the number of parameters, the selection of the initial parameters to be investigated is usually based on intuitive reasoning, previous research, pilot studies and the practicality of measurement. The final parameters in the model are then based on statistical significance, which in turn depends on experimental design and sampling considerations. Strong correlations between certain roundabout parameters (e.g. entry width and circulation width) can also affect their statistical significance.

Many empirical models are likely to have been constrained by the sample sizes used for model development, which would have been limited by the number of congested roundabout entries available. Statistically-significant relationships between capacity and geometric parameters could also have been difficult to identify due to the limited range of observable parameter values. For example, saturated conditions at a roundabout entry usually correspond with a limited range of circulating flows during peak hours, and this has partly led to the ambiguity over the Q_e,Q_c relationships being linear or non-linear.

The above issues probably explain why despite examining a range of geometric parameters, no other parameter aside from Q_c was found to be consistently significant across various regression models found in published literature (Leemann and Santel, 2009; Transportation Research Board, 2007; Al-Masaeid and Faddah, 1997; Polus and Shmueli, 1997; Brilon and Stuwe, 1993; Louah, 1992; Stuwe, 1991; Semmens, 1988; Semmens, 1982; Kimber, 1980; Glen *et al.*, 1978; Kimber and Semmens, 1977). The results of any empirical model are also likely to be reliable only within the range of parameters in the original database used to develop it. An example was the inability of the LR942 model to satisfactorily model entries with heavily-unbalanced lane utilisation (Chard, 1997), which has since been rectified with simulation-based lane modelling in ARCADY / Junctions 8 (TRL Software, 2012). Also, entry capacities at very high circulating flows likely involve extrapolation and may thus be less accurate, since regression models are best-suited to ‘average’ conditions relative to the original dataset.

The issue of extrapolation may also affect the transferability of regression-based models to other countries due to differences in roundabout layouts or driver behaviour (Brilon, 2011; Transportation Research Board, 2007; Troutbeck, 1998; Kimber, 1989). To compensate, calibration of the models through changes to coefficients such as slopes and intercepts could be used if actual capacity data is available. However, such adjustments are acceptable only to a limited extent, as major changes to the layouts would involve other changes to the model parameters which may not be clearly understood.

2.2.4 Gap acceptance capacity models

Gap acceptance is an alternative approach to modelling capacity, based on theoretical models developed around parameters obtained from measurements of individual headways between circulating and entering vehicles. The data collection for this method is thus less contingent on heavily-congested entries with continuous queuing compared to that for empirical models (Akçelik *et al.*, 1998, pp.11-12; Rodegerdts *et al.*, 2006, pp.B20-B21).

Gap acceptance models rely on three variables to determine entry capacity:

- Critical gap (t_c) is the minimum time headway in the circulating stream which an entering driver will accept, and is thus also called *critical headway* in some literature (e.g. Transportation Research Board, 2010a). As critical gap cannot be observed directly, many methods have been developed for its estimation from observed rejected and accepted headways/gaps, such as those of Siegloch, Raff, Harders, Wu and others (Brilon *et al.*, 1999; Wu, 2012).

- Follow-on headway (t_f) is the time headway between two consecutive queued vehicles entering the same gap in the circulating stream.
- Distribution of gaps in circulating flow is based on Poissonian random arrivals or bunched flows. The M3 distribution of Cowan (1975) in particular has been widely-used to model circulatory headways for roundabouts (Akçelik, 2007; Luttinen, 1999; Hagring, 1996; Troutbeck, 1989) but its parameters have to be estimated from field-data as they vary according to driver behaviour (Tanyel and Yayla, 2003).

From these variables, the entry capacity can then be calculated through appropriate models. Early models included those by Tanner (1962), Armitage and McDonald (1974) and Ashworth and Laurence (1978), but the Siegloch model has been more widely-adopted, being the basis for the HCM 2010 (Akçelik, 2011a), early German models (Stuwe, 1991) and the French Girabase model (Certu, 2006). It is based on negative exponential headways, with critical gap and follow-on headways regressed from measurements in saturated conditions:

$$Q_e = \frac{3600}{t_f} e^{-Q_c\left(t_c - \frac{t_f}{2}\right)}$$

The diversity of gap acceptance models available is the result of differences in assumed headway distributions, and the formulation of the relevant parameters such as the proportion of bunching in the major priority flow (Akçelik, 2007; Wu, 2001). In addition, several models such as SIDRA and that of McDonald and Armitage (1978) use a traffic signal analogy with either lost times and saturation flows, or equivalent green and red times based on the distribution of gaps in the circulating flow (Akçelik, 1994). Comparisons by Akçelik (2007) of several of these gap acceptance capacity models showed that there was generally little difference in the model outputs except at larger circulating flows where bunching became more significant.

2.2.4.1 U.S. Highway Capacity Manual 2010

Given the scarcity of congested roundabouts in the 1990's, roundabout capacity modelling in the U.S. was initially based on the LR942 model with default geometric parameters (Federal Highway Administration, 2000), although the Harders gap acceptance model was also adopted in the 2000 Highway Capacity Manual (HCM) with default upper- and lower-bound critical gap and follow-on headways (Transportation Research Board, 2000).

Later research identified equivalence between the coefficients of an exponential model regressed from capacity data from 18 single-lane and 7 two-lane approaches, and those corresponding to field-measured critical gap and follow-on headway values using the Siegloch model form (Transportation Research Board, 2007; Akçelik, 2011a). These findings thus formed the basis of the HCM 2010 model (Transportation Research Board, 2010a) shown in Figure 2-3, which could be calibrated with measured gap acceptance parameters. However, inadequate evidence of statistically-significant relationships between capacity or gap acceptance parameters and other geometric variables meant that the exponential model coefficients depended only on the number of entry and circulating lanes, and whether the entry lane is nearside or offside.

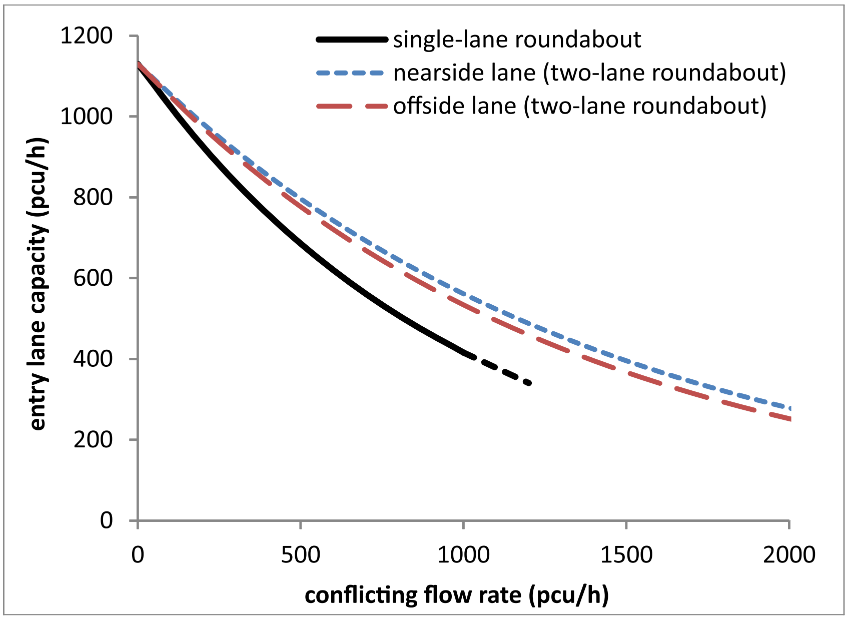


Figure 2-3 HCM 2010 roundabout lane entry capacity relationships (adapted from Transportation Research Board, 2010b).

2.2.4.2 German HBS 2001 / Brilon-Wu

Early studies into German roundabout capacities were initially based on gap acceptance models, but had difficulties such as the definition of the major stream at multilane roundabouts (Stuwe, 1991). Later approaches used regression analyses with an exponential form with a total sample size of 4898 one-minute intervals from one- and two-lane entries entering roundabouts with 1- to 3-lane circulation (Brilon and Stuwe, 1993). This was later changed to a better-fitting linear form when the sample size was increased to 7252 data points (Brilon *et al.*, 1997). However, the linear model was rejected as it did not have a clear theoretical basis, while there was doubt over its validity at flows where few measurement points were available (ibid.).

The model as used in the German Highway Capacity Manual 2001 was derived from gap acceptance principles and queuing theory (Wu, 2001), and based on the numbers of entry (n_e) and circulating (n_c) lanes:

$$Q_e = 3600\left(1 - \frac{\Delta Q_c}{n_c 3600}\right)^{n_c} \frac{n_e}{t_f} e^{-\frac{Q_c}{3600}\left(t_c - \frac{t_f}{2} - \Delta\right)}$$

The default values of critical gap (t_c), follow-on headway (t_f), and intra-bunch minimum headways (Δ) were initially obtained from field observations (Brilon, 2005), but the draft of the upcoming German Highway Capacity Manual will use diameter-dependent values for single-lane roundabouts of 26 to 40 m diameter (Brilon, 2014). Larger roundabouts will use exponential model coefficients which are directly regressed instead of using the above equation (ibid.).

2.2.4.3 SR45/ SIDRA gap acceptance model

The best-known gap acceptance model for roundabouts was developed in Australia, introduced initially in the form of the SR45 model (Troutbeck, 1989). Using data from 55 roundabout entry lanes in Australia, regression equations were developed for critical gaps (t_c) and follow-on headways (t_f) of the dominant and sub-dominant lanes of an entry (Troutbeck, 1989). The dominant lane in a multi-lane entry was defined as the lane with the larger demand flow, the larger turning flow, or else that in the offside position (Akçelik, 1997).

The circulating headway distribution was the Cowan M3 distribution, where a proportion of vehicles (α) was assumed to be bunched with a fixed intra-bunch headway (Δ), while remaining vehicles had exponentially-distributed headways. The intra-bunch headway was taken to be 1 second for multilane circulation, and 2 seconds for single lane circulation, while the proportion of bunched vehicles was calculated from the circulating flow using regressed equations (ibid.). The entry capacity for each lane was then calculated from (Troutbeck, 1989):

$$Q_e = \frac{\alpha Q_c e^{-\lambda(t_c - \Delta)}}{1 - e^{-\lambda t_f}}$$

where λ is a scale parameter or decay rate which depends on Δ, α and Q_c.

The SIDRA model (Akcelik & Associates Pty Ltd, 2013) is a further development of the SR45 model using a traffic signal analogy (Akçelik, 1994) and revised versions of the empirical follow-on headway and critical gap equations from SR45. Other revisions to the circulating headway and capacity models included additional factors for priority-sharing, origin-destination patterns and queuing on upstream approaches (Akçelik and Besley, 2004; Akçelik *et al.*, 1998) which were calibrated from studies based on microscopic simulator ModelC (Akçelik *et al.*, 1997). The latest version of SIDRA Intersection now includes adjustment factors for entry radius and entry angle (Akçelik, 2011c).

2.2.4.4 Limitations of the gap acceptance approach

Priority-sharing occurs when circulating vehicles slow down to accommodate and avoid colliding with vehicles which forcibly enter smaller gaps; in extreme cases, priority-reversal occurs where some circulating vehicles are temporarily stopped due to gap-forcing by entering vehicles or blocked exits. These phenomena occur to varying extents at many roundabouts, particularly when circulating vehicles travel at relatively slow speeds with lower braking distances. Their occurrence contradicts the common assumption in gap acceptance methods of circulating headway distributions not being affected by entering vehicles (Kimber, 1989), but modifications to headway distributions (Troutbeck and Kako, 1999; Akçelik, 2011b) and flow-dependent critical gap models (Troutbeck, 1989) have been developed to overcome this problem.

One criticism of gap acceptance based models is that they do not directly quantify the relationship between geometry (the only factor which can be controlled by the roundabout designer) and capacity. Instead, they require the formulation and calibration of an intermediary vehicle-vehicle interaction model, which then has to be related separately to geometry and entry capacity. This is an issue as capacity models are sensitive to the values of critical gap and follow-on headway, as well as differences in headway distributions at higher circulating flows (Akçelik, 2007). However, the inherent variability of driver behaviour results in fairly weak relationships between these parameters and geometry due to the influence of other factors. For example, critical gap at roundabouts has been found to vary with delay (Polus *et al.*, 2005; Polus *et al.*, 2003) and circulating speed (Xu and Tian, 2008), while Hagring (2001) suggested that the critical gap could be overestimated if the proportion of vehicles exiting just before the entry was large. By including only more tractable geometric and flow parameters, the regressed equation for critical gap in the SR45 model explained less than half of the observed variation (Troutbeck, 1989). And in contrast to SR45 / SIDRA and CAPCAL models (Allström, Hagring and Linderholm, 2006 cited by Linse, 2010; Hagring, 1997a), the critical gap in most other gap acceptance models is insensitive to geometry.

There are also difficulties with defining the parameters from field-measurements. For example, gap acceptance headways can be difficult to define in multilane circulation flows as vehicles on the inner[1] circulating lane may be perceived to conflict with drivers entering the outer lane (Hagring, 2000b; Troutbeck, 1990); likewise, arrival times at the give-way line for lag measurements are difficult to measure since approaching drivers can adjust their speed on the approach to intercept gaps in the circulating flow without having to stop at the give-way line (Louveton *et al.*, 2012b; Louveton *et al.*, 2012a; Weinert, 2000; Hewitt, 1983). Furthermore, there are many methods of calculating critical gap, but they do not give consistent answers (Tupper *et al.*, 2013; Wu, 2012; Lindenmann, 2006; Brilon *et al.*, 1999). Similarly, the intra-bunch headway (Δ) and the proportion of bunched vehicles (α) used in bunched headway models cannot be measured directly, given that the distinction between free-flowing and platooned vehicles is not always clear from their headways. α is usually based on various functions of circulating flow and Δ (Akçelik, 2007). Multilane circulation has typically been approximated as a single stream (Akçelik *et al.*, 1998; Hagring, 1996; Troutbeck,

[1] For circulating lanes, this thesis uses the terms "inner" and "outer" based on position relative to the centre of the roundabout.

1989), where Δ is taken to be a fixed value depending on the number of circulating lanes (Troutbeck, 1989) or in SIDRA's case, a function of circulating lane flows, origin-destination and approach queuing patterns (Akçelik *et al.*, 1998). These approximations have been justified by the need to model larger gaps more accurately compared to smaller gaps and for greater tractability (Luttinen, 1999; Troutbeck, 1991), but they can also mean that calibrating the models with new field-measured values for a different layout or context may not be trivial (Tanyel and Yayla, 2003).

2.2.5 Microscopic simulation models

Microscopic simulation models are based on modelling the movements and interactions of individual vehicles on a network consisting of links and nodes or connectors. Vehicle movements are governed by gap acceptance, car-following, lane-changing and other models, and are typically calculated for each vehicle at every specified time-step. Driver behaviour parameters such as critical gaps, and processes such as vehicle generation are stochastically assigned through Monte Carlo methods using specified probability distributions; the resulting variability of outputs attempt to reflect the characteristics of real-world traffic.

Several proprietary microscopic simulation programs are available for the modelling of general traffic networks, including S-Paramics (Paramics Microsimulation, 2011b), Aimsun (TSS-Transport Simulation Systems, 2011), Vissim (PTV Group, 2013b), and SUMO (DLR Institute of Transportation Systems, 2001-2014). Several roundabout-specific microscopic simulation models have also been developed and used for research (Chung *et al.*, 1992; Tan, 1991; Chin, 1985; Krogscheepers and Roebuck, 1999), while other simulation programs such as INSECT (Tudge, 1988), OCTAVE (Louah, 1988) and KNOSIMO (Grossmann, 1988) have been used for analysing unsignalised junctions in general.

One advantage of microscopic simulation models is that demand flows and turning movements can be controlled for parametric studies. They are thus used in roundabout research which requires such effects to be modelled (Valdez *et al.*, 2011; Fortuijn, 2009b; Krogscheepers and Roebuck, 2000), as well as for the development and the validation of macroscopic models such as SIDRA (Akçelik, 1997). Bared and Afshar (2009) and Hossain (1999) also derived macroscopic capacity models through regression of data from microscopic simulation models rather than from field data. Simulation models have also played an important role in the modelling of the effects of flaring on capacity (Burtenshaw, 2012; Wu, 1999). The role of simulation models in roundabout capacity modelling is illustrated by the development of the Swiss capacity model.

2.2.5.1 Swiss Bovy-Tan model

The Swiss roundabout capacity model was based on the French CETUR linear empirical model (Louah, 1988), with the slope and intercept calibrated to Swiss field-observed and simulated data respectively (Tan, 1991):

$$Q_e = 1500 - \frac{8}{9}(\beta Q_c + \alpha Q_x)$$

Where β depends on the number of circulating lanes, and α attempts to reflect the impact of vehicles leaving the roundabout (Q_x) immediately upstream (on the circulating carriageway) before the point of entry (see Figure 2-4). Through microscopic simulation, it was found that α decreased with the separation distance between the point where circulating and exiting streams diverge and the point where entering and circulating streams merge (Tan, 1991).

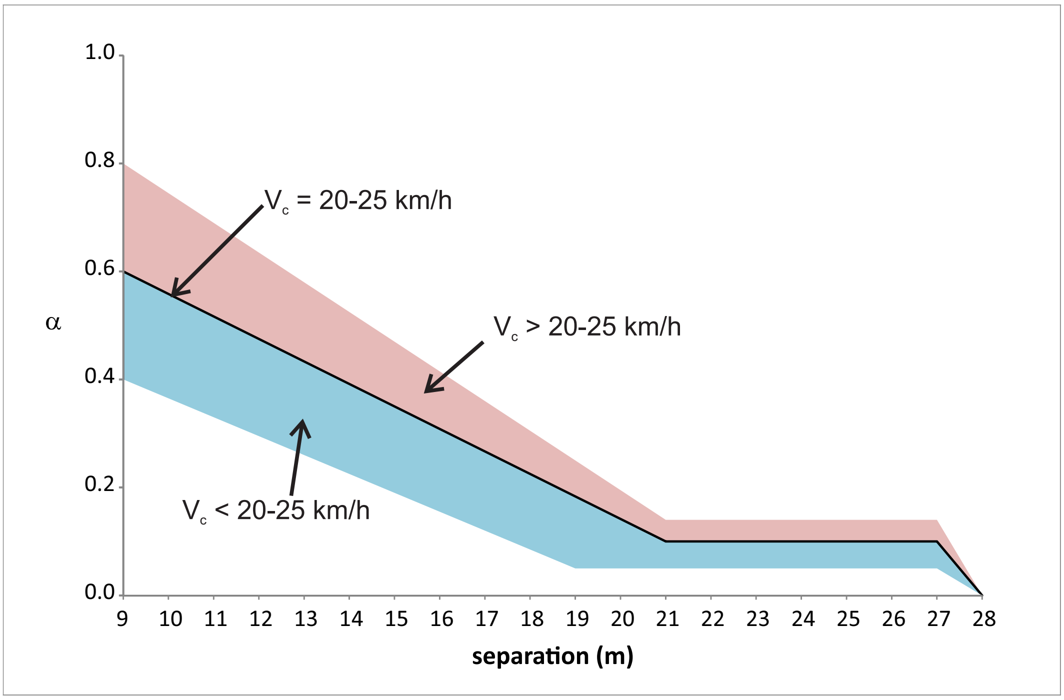


Figure 2-4 Relationship between the exiting flow coefficient α against the separation distance between the entry and the exit of the arm; V_c represents speed of circulating vehicles (adapted from Simon, 1991).

However, more recent research into the capacity for Swiss multilane roundabouts has been mainly empirical rather than simulation-based (Lindenmann *et al.*, 2009).

2.2.5.2 Limitations to microscopic simulation

The most widely-acknowledged limitation of microscopic simulation modelling of roundabouts is the priority-reversal and priority-sharing phenomena. While the former may arise due to capacity restrictions of other junctions downstream and is thus beyond the scope of this paper, the more subtle issue of priority-sharing, which occurs especially at high circulating flows, does need to be considered. Relatively simple gap acceptance algorithms used in common microscopic simulation programs may not adequately model the effect of priority-sharing (Chevallier and Leclercq, 2009a), resulting in the under-prediction of entry capacities at high circulating flows. Hence, more complex multi-level gap acceptance algorithms, or alternatives such as the probabilistic gap acceptance algorithm of Chevallier and Leclercq (2009b), may be required to model roundabout capacity more accurately in congested conditions.

The above is illustrated through a case study based on traffic data from a field survey (described in greater detail in Chapter 3), using S-Paramics software which was developed and calibrated to the U.K. environment (Paramics Microsimulation, 2011a). A model of the single-lane, east entry of the A33 / B3349 roundabout in Berkshire was developed (Figure 2-5), using default driving behaviour parameters and link visibility parameter of 20 m based on on-site observations. The east entry was loaded to queued, capacity conditions while the vehicle mix and turning proportions were based approximately on those recorded from the actual roundabout. In multiple simulation runs with random seed numbers, the circulating flows across the east entry were varied, and measurements of entry flows and circulating flows were made in one-minute intervals when queueing was present at the east entry. As shown in Figure 2-6, it is clear that capacity was underestimated at high circulating flows, suggests that the model did not adequately account for priority sharing often observed in congested real-world roundabouts (Troutbeck and Kako, 1999).

Some microscopic simulation models also have difficulty in accurately modelling the behaviour at multi-lane entries. For example, in a roundabout with two-lane entries and circulation, there is in theory no conflict between a nearside entering vehicle and a vehicle on the inner circulating lane, as they can circulate two abreast. A microscopic simulation network which reflects this, such as that shown in Figure 2-7 based on the A33 / B3349 roundabout network above, would produce a higher entry capacity for the nearside entry lane as it only conflicts with vehicles in the outer circulating lane rather than in both circulating lanes.

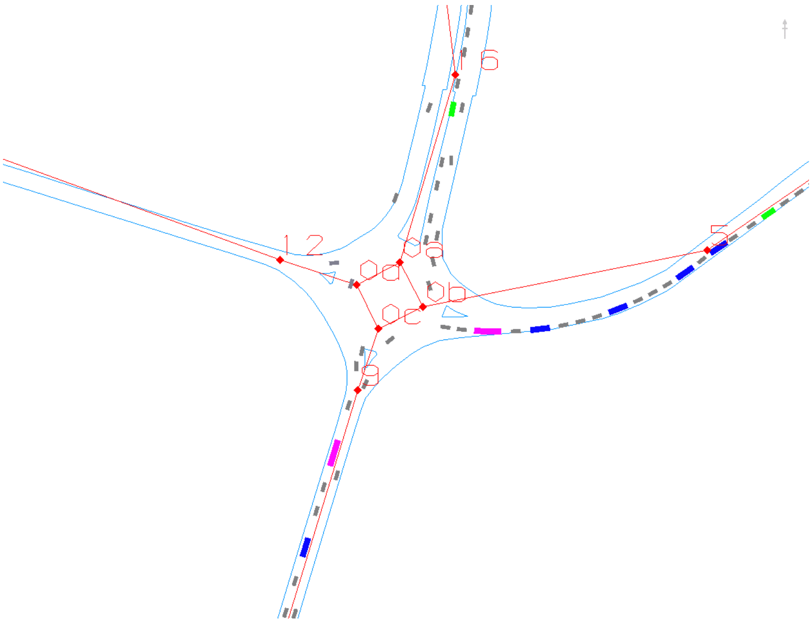


Figure 2-5 S-Paramics model of A33 / B3349 roundabout, with east entry loaded to capacity.

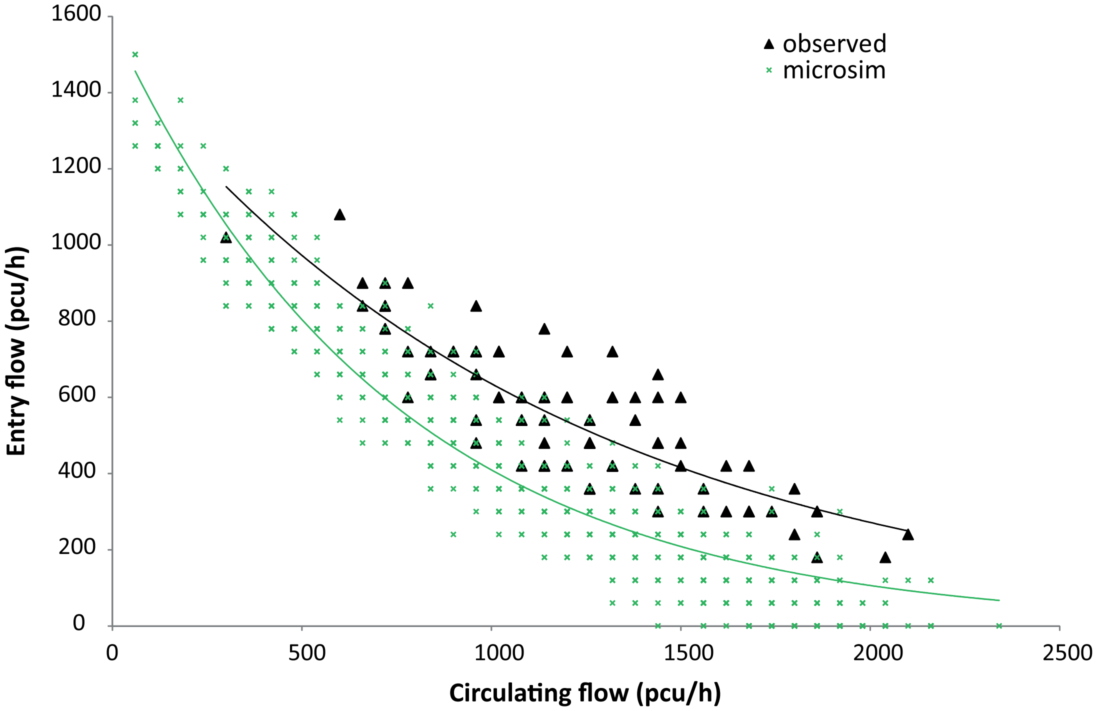


Figure 2-6 Comparison of observed one-minute capacity flows from A33 / B3349 roundabout East entry with those from S-Paramics model using default parameters.

However, in practice, it is often observed that vehicles in the nearside lane do not enter when there is a circulating vehicle on the inner lane (Troutbeck, 1990), as there is usually some uncertainty over whether that vehicle will change to the outer lane to exit at the next arm. The artificial insertion of a conflict point in the microscopic simulation model is a possible solution to replicate this, but does not accurately portray the actual situation where some nearside drivers do occasionally enter. Cicu *et al.* (2011) used a reduced critical gap value for the nearside entry lane, but a more realistic representation would probably require a bespoke probabilistic algorithm and a better understanding of the driver decisions.

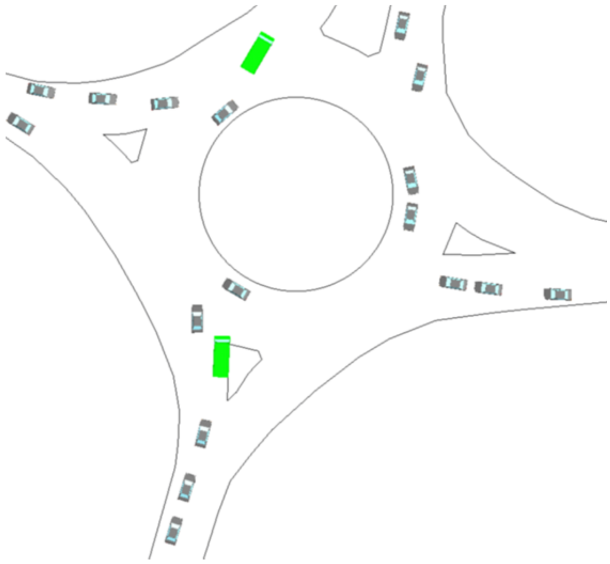


Figure 2-7 Example microscopic simulation model set up to show a car entering from nearside lane alongside another circulating in inner lane, while a heavy vehicle waits in the offside lane of the bottom arm.

The outputs of microscopic simulation models depend on a large number of different parameters which govern the vehicle movements. Despite promising developments in computer vision or digital video analysis for determining vehicles speeds and trajectories in roundabouts and junctions (Tageldin *et al.*, 2014; St-Aubin *et al.*, 2013b; Mussone *et al.*, 2011; Guido *et al.*, 2011; Wei *et al.*, 2005; Inman *et al.*, 2003), many of the parameters can be difficult to calibrate from available field data, and so may be left as default values recommended by the software developers. Calibration and validation of the models are thus crucial to ensure the suitability of these parameters, and these are typically performed through comparisons of the model outputs with field data at an aggregate level, using measures such as journey times, turning flows and speeds (Li *et al.*, 2013; Wei *et al.*, 2012; Cicu *et al.*, 2011; Duong *et al.*, 2011; Vaiana and Gallelli, 2011; Ryder, 2001).

For calibration, the most important aggregate measure is likely to be the entry flows at capacity conditions for the given circulating flows. However, entry capacity is sensitive to the critical gap value (Gallelli and Vaiana, 2008), other parameters such as minimum headways, acceleration rates, reaction times, turning speeds, vehicle lengths and visibility distances (Casas *et al.*, 2010; Fellendorf and Vortisch, 2010; Sykes, 2010) and potentially simulation time step size (which reflects gap acceptance reaction time); indeed, for the case study above, the capacity throughputs could be further adjusted specifically through vehicle swept paths, stop line positions, opposing vehicle flows and visibility for manoeuvres (Sykes, 2010, p.153). However, even if model parameters such as these were optimised for output flows, there can often be trade-offs in accuracy for other outputs (Duong *et al.*, 2011), reflecting the approximations inherent in the assumed vehicle behaviour and interaction rules in microscopic simulation.

For proposed designs with no field data available, it is necessary to apply the adjusted parameters from another existing roundabout model which has been validated with field data. It is however questionable whether such calibrated parameters can be transferred directly from one roundabout to another (Gagnon *et al.*, 2008) particularly when the geometry and flows are different, as the issue (identified above) remains that there is no direct link between geometry and gap acceptance behaviour.

2.3 Discussion

2.3.1 Differences in inputs and their implications

The limitations of each of the major capacity modelling approaches, as discussed above, mean that the development of the major capacity prediction models has usually involved a combination of two or more approaches. However, given that roundabouts are designed and operate on very similar principles, the inconsistency of significant variables in the models (Table 2-1) suggests the possible omission of influential variables due to methodological or sampling constraints. If so, this means that the models likely do not provide a full description of the complex behavioural and physical processes which govern entry capacity at roundabout entries.

Table 2-1 Comparison of principal inputs shared by major international roundabout capacity models

Input variable	HCM 2010	German (Brilon-Wu)	French (Gira-base)	LR942 model	RR142 model*	SIDRA Inter-section 5.1	Swiss (Bovy-Tan)
circulating flow	Included	Included	Included	Included	Included	Included	Included
inscribed circle diameter or radius	-	Included	Included	Included	Included	Included	-
entry-exit separation or splitter island width	-	-	Included	-	Included	-	Included
no. of circulatory lanes or circulatory width	Included	Included	Included	-	-	Included	Included
no. of entry lanes	Included	Included	-	-	-	Included	Included
entry width	-	-	Included	Included	Included	Included	-
approach half width	-	-	-	Included	Included	-	-
effective flare length or short lane length	-	-	-	Included	Included	Included	-
entry curvature i.e. 1/entry radius	-	-	-	Included	Included	Included	-
entry angle	-	-	-	Included	Included	Included	-
lane position in entry or lane dominance (for lane-based models)	Included	n/a	n/a	n/a	n/a	Included	n/a
exiting flow	-	-	Included	-	-	-	Included

* ARCADY empirical model for grade-separated or diameter>130m roundabouts (Semmens, 1988)

Further evidence of this is shown by the fact that even when the above models shared a common input variable, there was disagreement over its functional relationship with entry capacity. For example, the LR942 model had a linear Q_e,Q_c relationship whereas the others were based on various exponential forms. The impact of increased diameter was to increase capacity at higher Q_c in LR942, but the SIDRA model showed a decrease at large diameters. Larger exiting flows had a wholly negative impact on capacity in the Bovy-Tan model, but the Girabase model found that their impacts could be positive depending on other variables. However, there was more agreement between LR942 and SIDRA for lane or entry width, entry angle and entry curvature; lower widths and larger angles or curvature resulted in reduced capacity.

2.3.2 The role of empiricism and its implications

The inability of the models to fully describe processes at roundabout entries is also reflected in their extensive reliance on field data from their countries of origin. Even the SR45/SIDRA gap acceptance model relies on empirical regression models for critical gap and follow-on headways. The reliance on empirical data in the calibration and/or derivation of the models raises questions over the geographical and temporal transferability of all the models. This is a concern as roundabout designs – and possibly driving behaviour – have gradually evolved with time. For example, after the conversion of 'conventional' roundabouts to offside priority in the U.K., designs have changed from short multi-lane flares with small islands to longer flares with fewer lanes. Larger roundabouts with higher entry capacities also became increasingly important, as shown by trends in research (Bared and Afshar, 2009; Leemann and Santel, 2009; Semmens, 1988; Semmens, 1982). Safety is an important driver for changes, as shown by the introduction of compact single-lane roundabouts designs into the U.K. by TD 16/07 for improved cyclist and pedestrian safety (Department for Transport, 2007b) and the growing consideration of turbo-roundabouts (Brilon, 2011; Fortuijn, 2009a; Giuffrè *et al.*, 2009).

These changes in designs have implications on the choice of the model for capacity analysis. For example, it may not be reliable to analyse turbo-roundabouts with most of the models above, since the Swiss model was validated with data mainly from single-lane roundabouts (Tan, 1991), while the French, German, HCM 2010 and the U.K. models were based on data from normal roundabouts.

2.3.3 Differences in methodologies and their implications for modellers

The fundamental methodological differences between the modelling approaches must also be considered when selecting a model for capacity analysis. There is no clear answer to which of the three modelling approaches is the best for all situations, although some models will be more suited to certain scenarios compared to others.

For example, as empirical models are developed from a database of roundabouts within a particular set of conditions, their use is likely to be more efficient and appropriate when the roundabout to be analysed is similar to those within the original model database in terms of geometry, traffic, driver, vehicle and other characteristics. On the other hand, if the circulating flow headways are highly unusual (e.g. due to platooning by upstream signals or unusual origin-destination and flow patterns), gap acceptance models may be more suitable. Simulation models may be required in cases with entry lane starvation in flared entries, given the need to explicitly model lane usage, the stochastic nature of the queuing and arrivals process, and the interaction with flare lengths. Referring to the example of new turbo-roundabouts where vehicles from the offside entry lane cross rather than merge with circulating flow, models based on gap acceptance or microscopic simulation could be more suitable, although careful calibration of the gap acceptance parameters would almost certainly be required (Mauro and Branco, 2010; Fortuijn, 2009b).

Such considerations are less clear when differences in driver populations are involved. Gap acceptance models are probably more sensitive to differences in driver and traffic characteristics manifested in altered critical gaps, follow-on headways and headway distributions. However, part of the observed differences in these values could be due to differences in site layouts rather than driver behaviour alone, and these cannot be distinguished unless measurements were obtained from identical layouts. Hence, it is not always clear which method would be more transferable in such circumstances.

2.3.4 Differences in model outputs and the role of calibration

A major component of capacity model errors arises from the variability of driver and traffic behaviour in the gap acceptance process, as reflected by the poorer capacity predictions for junctions with gap-acceptance relative to those for signalled-controlled junctions (Kimber, 1989). The LR942 capacity estimates for a typical site had a standard error of about 15% or 200 pcu/h at the mean Q_e of 1300 pcu/h (Kimber, 1980). The 95% confidence limits for SIDRA were about 105 veh/h for the same Q_e, although it should be noted that this excluded any errors in predicting critical gap and follow-on headway (Akçelik *et al.*, 1998) which are unlikely to be small for the reasons discussed above. It is not clear what the equivalent errors are for other models, but the size of such errors suggests that the inclusion of additional variables could potentially improve their ability to explain all the processes at the roundabout entries.

Several studies have compared the predicted capacities of the same roundabouts from different models, using their uncalibrated form:

- Özuysal *et al.* (2009) found that the LR942 model under-predicted the capacity of Turkish single-lane roundabouts, and produced poorer predictions compared to the German model of Stuwe (1991). In contrast, the SR45 equations under-predicted critical gap and follow-on headways.
- Transportation Research Board (2007) found that all the major models reviewed earlier in this paper over-predicted the capacity of 25 U.S. roundabout entries, with only one being under-predicted by the German model.
- Polus and Shmueli (1997) found that the LR942 regression model predicted higher capacities for the Israeli roundabouts in their sample when compared to German, Australian and Swiss models. The German model was particularly close to the observed capacities.
- Troutbeck (1998) found that the German linear empirical model produced much lower predicted capacities compared to the U.K., Troutbeck and SIDRA models, based on a hypothetical roundabout.
- Stanek (2012) compared the HCM 2010, SIDRA, Vissim and Paramics models on a hypothetical roundabout and found differences in the entry capacities ranging from around 620 to 260 veh/h at circulating flows of 0 and 1000 veh/h respectively.

Given the relative similarity of roundabout designs worldwide, the differences above are probably the result of the different sources of empirical data used in the development and calibration of the models, particularly that of driving behaviour. For example, the U.S. HCM 2010 model has larger default critical gap and follow-on headways compared to other countries, perhaps reflecting the fact that U.S. drivers are the least experienced in the use of roundabouts (Transportation Research Board, 2007), or that U.S. vehicles are generally larger than those used in Europe. Differences in capacities between different countries have been attributed to different lengths of roundabout experience (Mauro, 2010; Transportation Research Board, 2007; Troutbeck, 1998), although these differences could diminish as drivers gradually get more accustomed to using roundabouts (Johnson, 2013; Wei *et al.*, 2011).

Most of the models thus have a calibration facility, such as the intercept correction of ARCADY / Junctions 8 (Burtenshaw, 2012), the Environment Factor of SIDRA (Akçelik, 2011c), the critical gap and follow-on headway adjustments in HCM 2010 (Transportation Research Board, 2010a, ch.33), and the vehicle behaviour model parameters in microscopic simulators. However, as discussed previously in sections 2.2.3, 2.2.4.4 and 2.2.5.2, there are several issues associated with the calibration of each of the three modelling methodologies. Furthermore, Gagnon *et al.* (2008) compared several macroscopic and microscopic models and found that the calibrated parameters used in each model are likely to be site-specific. This would be an issue as the determination of those parameters requires data from roundabouts which are local and/or have similar characteristics, which may not be available with proposed designs.

The differences between the models' outputs and observed conditions can be reduced through calibration, and several studies have applied recommended calibration methods to compare the models against hypothetical or actual data:

- Akçelik (2011b) compared the LR942, HCM2010 and SIDRA models based on a hypothetical single-lane roundabout in U.S. conditions; the difference in predicted capacities from the calibrated models was around 100-220 veh/h except at low circulating flows. Such differences would then have been magnified through RFC values at higher circulating flows, with potentially large effects on predicted queues and delays.

- Lenters and Rudy (2010) investigated several methods of calibrating the linear LR942 model to fit the HCM2010 regression model including curve-fitting solutions and the default method of intercept correction. Given the shortcomings of these methods, they concluded that the best approach was a general recalibration of the LR942 model for U.S. conditions which can only be possible with more data from congested U.S. roundabouts.
- Transportation Research Board (2007) calibrated the major models discussed in this paper with approach-specific gap parameters or intercepts, and compared them with measured capacity flows from 22 approaches. The use of site-specific calibrated values provided a better fit than would have been possible with field average values, even though the latter were more likely to be relevant in practice especially for new sites. Nevertheless, although the overall model errors were significantly reduced compared to their uncalibrated forms, it was found that new exponential regression models showed better performance compared to the calibrated models. Hence, the regression models were chosen as the basis of the HCM2010 model.

These observations indicate that calibration with local or comparable data may have only a limited impact in improving the predictive ability of models in new contexts. A key limitation of calibration methods is an incomplete understanding of how model parameters change with capacities and inputs in all the models. While calibration parameters (such as LR942's intercept, SIDRA's Environment Factor, or the priority rule parameters of microsimulation models) enable the model-predicted capacities to be matched to observed capacity flows, it is not always clear how the resulting changes in the outputs relate to changes in the model coefficients or inputs. For example, it is not clear how these calibration parameters should be changed to reflect major adjustments to a roundabout's geometry, once they have been calibrated to an existing set of geometric and traffic conditions for that roundabout. An understanding of the calibration mechanism and how it relates to the model inputs and outputs is essential for the model to be truly transferable to other contexts or designs.

2.4 Chapter conclusions

A review of the existing literature on roundabout capacity modelling has allowed roundabout entry capacity in the context of this research to be defined, as well as various conditions for its measurement. Three main methodologies which form the basis for major roundabout capacity models were then critically reviewed. Empirical models map the relationships between capacity and significant input variables, but are subject to statistical and sampling constraints. Gap acceptance models are based on models of driving behaviour and traffic characteristics, but are limited by the relatively weak relationships between these models and geometry. Stochastic microscopic simulation models provide the greatest flexibility, but they heavily depend on an accurate representation of vehicle-vehicle interactions which can be difficult to replicate, even with actual observations.

The various limitations and inherent approximations in these methodologies prevent them from fully explaining the highly complex processes at roundabout entries. This on its own is not a problem, as the main aim of capacity models is to produce reasonably accurate estimates of capacity rather than an exact and rigorous description of the processes involved, given the inherent variability of driver and vehicle characteristics. However, these issues mean that all the major models rely on semi- or fully-empirical bases, using data from their countries of origin to quantify relationships between various parameters or to calibrate fitted coefficients. Aside from causing differences in the predicted capacities between the models, the empirical bases also mean that none of the models should be used outside the range of the original database without consideration of the need for updated calibration, and this applies in terms of new designs, locations or perhaps even time periods.

Calibration with indigenous data has a limited ability to improve the transferability of the models, due to an incomplete understanding of the relationship between model parameters and capacity. Hence, historical trends suggest that only the redevelopment of the model through the inclusion of more empirical data will provide greater accuracy. The development of roundabout capacity models appears to have followed a similar pattern in many countries, typically beginning with the adoption of a basic model developed from other countries which have had greater experience with roundabouts. This is then calibrated with any available indigenous empirical data, such as critical gap and follow-on headway values for gap acceptance models, or corrections to the coefficients or intercepts of regression models. This is then followed by further development and calibration with empirical data from indigenous roundabouts, as capacity data became more widely available from an increasing number of congested roundabouts in the country.

Even this is an interim solution however, until a more complete understanding of the processes at roundabout entries can be developed. Until then, designers should be aware of the limitations of existing capacity models described here when they select a modelling approach, and particularly the issues which arise when analysing new designs or those in different contexts.

In the context of this research however, one key finding is that there appears to be little agreement in the literature over the factors and variables which have a significant influence on the entry capacity of roundabouts. Furthermore, even though all the models share the most important variable of circulating flow, there is no consensus over the form of its relationship with entry capacity, such as whether a linear or nonlinear representation is best.

These conclusions point to a need to improve the understanding of how the various factors and variables affect roundabout entry capacity, as an important step towards developing better roundabout capacity models.

Chapter 3: Empirical study design and data collection

As shown by the preceding chapter, there is a need to improve our understanding of the factors and variables which significantly affect capacity. This required the collection and analyses of ground truth data from the field, which would also allow existing capacity models to be evaluated. Any significant potential shortcomings in their predictive ability would then warrant the development of better alternative models, and the data could then also form the basis of these new models. This chapter thus describes the design of the sampling and data collection methods, and justifies why an empirical methodology was used as opposed to gap acceptance. It then describes the characteristics of the resulting final dataset, and discusses the possible limitations arising from the data collection process. The bulk of this chapter has undergone the peer review process and has been published as a journal paper: YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (in press) Models of Roundabout Lane Capacity, Journal of Transportation Engineering, ASCE, doi: 10.1061/(ASCE)TE.1943-5436.0000773.

3.1 Hypothesised explanatory variables

The first step in this empirical study is identifying candidate independent variables affecting capacity, as they govern the sample design, data collection and hypothesis testing. At the microscopic level, the gap acceptance decision made by an individual driver at a roundabout entry will likely depend on various perceptual, cognitive, physiological and psychological factors, the characteristics of his/her vehicle, and those of the immediate environment including nearest conflicting vehicles. For example, various studies have shown that gap acceptance could be influenced by individual waiting time (Ashworth and Bottom, 1977), driver age and/or gender (Yan *et al.*, 2007; Teply *et al.*, 1997; Wennell and Cooper, 1981), oncoming vehicle size and colour (Alexander *et al.*, 2002), vehicle type (Teply *et al.*, 1997), conflicting vehicle speeds (Hancock *et al.*, 1991; Cooper *et al.*, 1977), sight distance obstruction by other vehicles (Yan and Radwan, 2007), driver distraction (Cooper and Zheng, 2002), risk aversion (Pollatschek *et al.*, 2002), presence of passengers or queued vehicles behind the subject coupled with delay at the front of the queue (Teply *et al.*, 1997). Human perception and cognition studies have also shown how factors such as the angle or curvilinearity of vehicle trajectories, visual references such as stop signs, and inherent perceptual styles could impact time-to-collision estimates (van Loon *et al.*, 2010; Berthelon *et al.*, 1998; Berthelon and Mestre, 1993) and thus possibly gap acceptance decisions. These factors may also influence follow-on headways, although gap interception likely plays an important role at roundabout entries since approaching drivers can control their speeds to merge into gaps in the circulating flow without having to stop at the give-way line (Louveton *et al.*, 2012b; Louveton *et al.*, 2012a).

Measuring and estimating many of these variables at a disaggregate level for capacity prediction is difficult, even if aggregated measures could be used to develop a more parsimonious model (in which the desired predictive performance was achieved with as few explanatory variables as possible). Macroscopic level variables are thus more commonly used in practice; for example, the critical gap model in SIDRA and SR45 is based on flow and geometric variables (Troutbeck, 1989; Akçelik *et al.*, 1998) rather than the factors described above. However, many of these variables (particularly geometry) do not yet have a clearly-understood effect on the gap acceptance process at the disaggregate level. Therefore, in the context of developing an empirical model with a limited dataset, including a very large number of such variables could increase the possibility of spurious results being obtained and over-fitting[2] of the model. Model validation would thus be essential, but it was also important to shortlist the more important explanatory variables to be investigated for inclusion in the final model; this was based on previous models and causal mechanisms suggested by existing literature. The shortlisted variables to be investigated and the rationale for their inclusion are described below and in Figure 3-1.

- Circulating flow, Q_c (pcu/hr): This is clearly the most important variable due to offside priority rule; essentially, the larger the flow, the smaller the headways and therefore the lower the frequency of gaps or lags of adequate size which can be accepted by entering vehicles.

[2] This is where the model fits or describes the 'noise' (i.e. random errors) in the sample rather than reflect just the actual underlying relationship between the variables.

- Wet weather (1=wet, 0=dry): Wet weather reduces entry capacity (Tenekeci *et al.*, 2010) since wet pavements may limit acceleration and speeds, while poorer visibility could also affect gap acceptance and follow-on headways.
- Queue duration, t_q (minutes): Proxy for average queue delay, where drivers may be more motivated to enter the roundabout when delayed. Larger driver delay or waiting time decreased critical gaps (Polus *et al.*, 2005; Polus *et al.*, 2003; Polus and Lazar, 1999; Ashworth and Bottom, 1977). However, Rodegerdts et al. (2007, p.52) found no evidence that queue duration was correlated with gap acceptance parameters.
- Lane width 10 m upstream, W_L (m): Lane width may be important as it reflects the available freedom of movement for approaching vehicles. For single entry lanes, flaring may allow zipper-like queue splitting and thus greater driver awareness for higher capacity, but this is likely to depend on a higher number of receiving circulation lanes than entry lanes. Effective flare length (l'), entry width (E) and approach half-width (V) were combined into the x_2 parameter in LR942 to represent the time-averaged number of queues (Kimber, 1980), but this was likely to be less relevant to individual lanes. The sharp curvature of most roundabout entries mean that the lane entry width at the give-way line may not be representative of the conditions experienced by a driver during the approach and gap acceptance process; Transportation Research Board (2007) did not find entry width to significantly affect lane capacity. An alternative measure which indirectly takes both flaring and lane widths into account is the lane width W_L measured 10 m upstream from the give-way line; this is comparable to the lane width 4 m upstream used in Girabase (Certu, 2006) or the 20-m-section-average lane width used in PICADY (Semmens, 1985; Semmens, 1980). Subsequent regression analyses with W_L generally showed better model fits compared to E.
- Inscribed circle diameter, D (m): Increases circulation speeds, possibly affecting perceived gaps and priority sharing. LR942 has a logistic relationship which suggests increased entry capacity at larger D, but Marstrand (1988) and Akçelik (2011c) found that entry capacity could reduce at large diameters.
- Entry angle, ϕ (°): Larger conflict angle requires greater turning motion and possibly limits acceleration i.e. less of a merging movement. May be offset by poorer driver visibility due to skew, but LR942 and SIDRA both show monotonous decrease in entry capacity with larger angles.

- Entry curvature, 1/r (m^{-1}): Higher curvature means entering vehicles may have to limit their approach speed or maximum merging speed and increase their minimum acceptable gap. Used in lieu of entry radius (r), since capacity is more likely to be sensitive to small radii than straight entries; LR942 and current SIDRA (Akçelik, 2011c) models show monotonous increase in entry capacity with straighter entries.
- Entry-exit separation, d_{sep} (m) and Exit flows, Q_x (pcu/hr): Although a few previous studies found that exiting flows or separation do not usually or significantly affect entry capacity (Troutbeck, 1990; Kimber, 1980; Ashworth and Laurence, 1978; Kimber and Semmens, 1977), others found a negative impact of exiting flow which improved with larger separation (Mereszczak *et al.*, 2006; Hagring, 2001; Louah, 1992; Tan, 1991). Separation distance or splitter island width was thus included in French (Guichet, 1997; Louah, 1992) and Swiss (Simon, 1991) models, while part of the exiting flow was concomitantly included in the conflicting flow. The conflicting flow also included exiting flows in the HCM 2010 and PICADY priority junction models (Transportation Research Board, 2010a; Kimber and Coombe, 1980), although this may have been due to their higher approach speeds.
- Distance to upstream entry, d_{upe} (m): This is also a proxy for the separation point between circulating and exiting vehicles originating from the upstream entry, where larger d_{upe} could facilitate earlier identification of an acceptable gap. The preceding entry is the nearest source of conflicting vehicles so the presence of a vehicle queued there could inhibit gap acceptance if d_{upe} was small; however, a vehicle departing from the preceding entry may also trigger gap acceptance since it is initially slower-moving than other circulating vehicles.
- Circulation width, W_c (m): The circulation width could alter the distribution of headways in the circulation flow by influencing the degree to which vehicles in adjacent lanes interfere with each other and hence whether the circulating stream was closer to a single-lane or multilane stream in terms of headway distributions (Troutbeck, 1989). It could also determine the distance between the give-way line and the merge conflict point, which may be a factor in deciding the minimum acceptable gap.

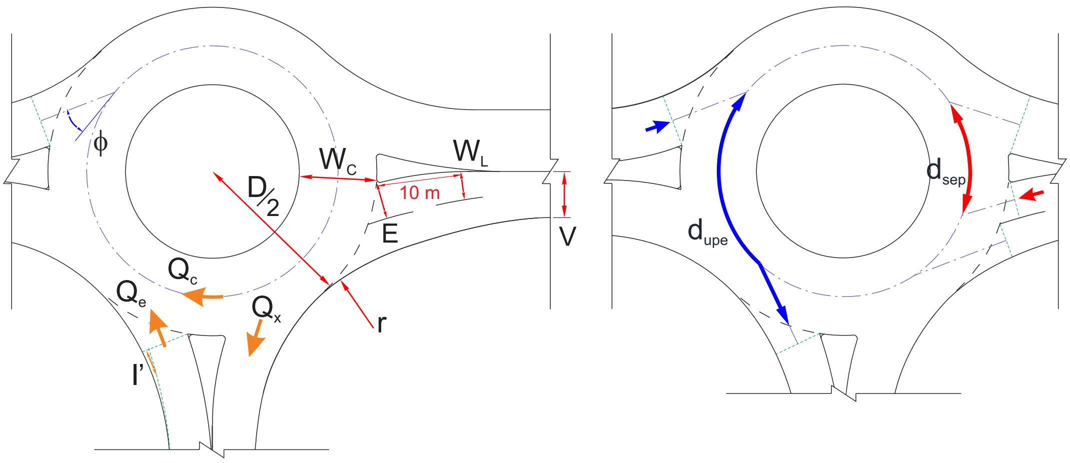


Figure 3-1 Measurement positions for predictor variables: flows and l' are for the bottom entry, ϕ and d_{upe} are for the left entry, while all other measurements are for the right entry.

Other variables were also considered in addition to the above, but could not be included in the study for various reasons. For example, departure sight distance and circulatory sight distance were considered as sight distances have been found to be a significant influence on capacity for priority junctions (Kimber and Coombe, 1980); however, there are practical difficulties in defining or obtaining accurate measurements at roundabout entries with live traffic. And given that drivers probably need to visually track multiple vehicles originating from both the circulation and the immediate upstream entries when making their gap acceptance decisions, it is unlikely that differences in sight distances could provide major improvements in capacity in congested conditions unless the sight distances were very low; however, this is unlikely given the minimum sight distances specified in design standards (Transportation Research Board, 2010b; Department for Transport, 2007b) for safety reasons.

Circulating lane usage and origin-destination (O-D) patterns have been suggested in various studies to have some influence on roundabout capacity (Akçelik, 2004; Krogscheepers and Roebuck, 2000; Hagring, 2000a; Guichet, 1997; Troutbeck, 1989). However, there is little agreement among these studies over the mechanisms by which lane usage or O-D patterns could affect entry capacity, and how they should be accounted for in capacity models e.g. whether through circulating headways or through lane-specific critical gaps. In practice, circulating lane usage is not easily determined due to frequent lane-changing and varying vehicle trajectories (St-Aubin *et al.*, 2013a; Mussone *et al.*, 2011; Salter and Al-Alawi, 1982), while the considerable resources required to collect ground truth O-D data at roundabouts (Dixon *et al.*, 2007; Mussone *et al.*, 2011) meant that it was beyond the scope of this study. These two variables were thus omitted.

The shortlisted candidate explanatory variables above deliberately omitted any headway-based variables such as critical gap and follow-on headways. This was because of the selected methodology to model the relationships between the hypothesised explanatory variables and entry capacity; gap acceptance modelling had been rejected in favour of empirical modelling based on direct capacity measurements. The reasons for this are explained in the following section.

3.2 Capacity modelling methodology

The capacity of a roundabout can be determined either directly from field-measured entry flows under saturated conditions, or by combining field-measured headways with theoretical gap acceptance models. The literature shows that the gap acceptance method is popular among roundabout capacity researchers worldwide, although this may have been necessitated to some extent by the lack of heavily-saturated roundabout sites in their countries (Rodegerdts *et al.*, 2006, p. B-20). However, the limitations of the gap acceptance approach discussed in section 2.2.4.4 mean that additional uncertainty could be introduced through the use of headways rather than flows, obfuscating the actual relationship between capacity and explanatory variables.

For example, a change in diameter may impact in different ways on circulating headway distribution, critical gap and follow-on headway; these three in turn determine the entry capacity in existing theoretical models. However, given that there is little consensus over the form and validity of these theoretical models among gap acceptance researchers, while quantifying the headway parameters typically involve various approximations, it would be far better to directly measure the capacity flows and relate them to differences in diameter. Furthermore, traffic flows can be easily and accurately measured compared to the time-of-arrival measurements necessary to calculate lags, so empirical modelling based on direct measurements of capacity flow has a clear advantage for quantifying the effects of factors and variables on capacity.

Aside from the analytical framework, there was also a need to consider whether to model capacity using lane capacities or arm capacities. To determine the entry capacity of a flared roundabout approach, the total entry flows should be measured when the queues extend to the throat of the flare with none of the lanes significantly starved of demand; however, these full arm-capacity conditions are rarely observed particularly with longer-flare entries, despite them having one or more lanes queued at the give-way line with measurable lane capacities. The total entry flows of flared entries are also subject to additional variability due to lane usage patterns (as discussed in section 2.1.2), which can only be accounted for with data from a range of origin-destination patterns, flare lengths and lane queue lengths from a much larger number of roundabouts. Given the limited resources available and the wider availability of lane capacity flow data, this study thus focussed on the factors and variables which affect gap acceptance capacity at the give-way line. The main limitation of basing the roundabout model on lane capacity is that the effects of flaring and lane utilisation will have to be modelled separately, using for example the Entry Lane Simulation model in Junctions 8 (TRL Software, 2012) or analytical solutions (Wu, 1999; Akçelik *et al.*, 1998, p.85).

3.3 Site selection and sampling

The limitations of the empirical modelling approach discussed in section 2.2.3 meant there were several important considerations in the design of data collection and sampling for this study. For example, the sampled data should ideally be representative of the population to which any ensuing model is to be applied, in terms of geometric as well as driver and vehicle population characteristics. However, in the U.K., each roundabout typically has a set of geometry, flows and O-D patterns unique to it, so appropriate selection of sites was critical to obtain a representative sample of data. This could be achieved through random or stratified sampling from the population of roundabouts (with strata based on roundabout size, for example), but the usable sample size is in practice constrained by several major factors:

- number of sites with measurable capacity based on the presence of saturated, queued conditions;
- sites with the desired range of hypothesised explanatory variables e.g. geometry, flow characteristics; and

- available resources for surveying.

Although previous relatively well-resourced, large-scale studies (Transportation Research Board, 2007; Kimber, 1980) had country-wide geographical distribution, the first two factors above remained major constraints. Unless track experiments with controllable geometry and flows (e.g. Kimber and Semmens, 1977) were used (despite their possibly questionable representativeness of real-world conditions), the second factor limited the observable range of input variables, particularly as the geometry of public roundabouts were constrained by design standards. However, older roundabouts which preceded these design standards were likely to have a larger variety of geometries, and can be found in the U.K. due to its pioneering use of modern offside-priority and older weaving-style roundabouts (Brown, 1995).

To reduce issues associated with the transferability of empirical models, the range of each of their included explanatory variables within the sample of sites should be as large as practically possible when sampling sites from the population. One exception was however the roundabout size. The scope of this research was limited to normal-sized roundabouts of between 30 to 100 m in diameter with non-traversable central islands, as previous research had shown that mini-roundabouts and very large and/or grade-separated roundabouts of greater than 130 m diameter have significantly different capacity models (Burtenshaw, 2012; Semmens, 1988) possibly due to different behavioural mechanisms.

In designing the sample, there was also a need to pre-empt analysis issues where possible. For example, statistical regression problems due to multicollinearity of predictor variables may arise from constraints on the roundabout geometry imposed by design guidelines, vehicle swept paths and geometric compatibility; this can be reduced by selecting sites to cover as wide a range as possible for each of the explanatory variables, and with respect to other variables. However, given the number of variables which have previously been found to affect roundabout entry capacity (as discussed in Chapter 1), sampling a wide range for all of them was not always achievable given the foremost criterion of having measurable at-capacity flows.

After considering the above criteria, desktop-based reconnaissance with live or historical traffic information (Google, 2012; Hampshire County Council, 2005) and local knowledge was used to identify roundabout entries which had long queues (both spatial and temporal). This was needed to maximise the yield of at-capacity data collected from the minimum necessary amount of survey sessions and resources. Although over 32 roundabouts were identified and monitored on weekday peak periods over several weeks, less than half appeared to be consistently congested for more than half-an-hour during peak traffic and/or on more than one arm. For these roundabouts, key geometric and other characteristics were assessed initially through aerial and street views in Google Earth (Google Inc., 2013) or Bing Maps (Microsoft Corporation, 2013) to produce a reasonably large range of geometric input variables in the sample. The sites in the final sample for data collection are listed in Table 3-1 and shown in Appendix A.

Table 3-1 Roundabout sites in sample

Roundabout reference name and entry arm(s) direction	Approximate location; major roads (geographic coordinates)
coralreef NW	Bracknell, Berkshire; A322 / B3430 (51˚23'27.46"N, 0˚44'4.01"W)
imperial SE	Reading, Berkshire; A33 (51˚25'5.63"N, 0˚58'33.30"W)
welshln S / E	Riseley, Berkshire; A33 / B3349 (51˚21'31.91"N, 0˚58'14.97"W)
baswinc SW / SE	Basingstoke, Hampshire; A340 / A30 (51˚15'18.43"N, 1˚ 6'13.08"W)
binfield NE / SW	Basingstoke, Hampshire; A33 (51˚17'7.66"N, 1˚ 3'41.16"W)
peacock NE / SE	Bracknell, Berkshire; A329 (51˚24'34.48"N, 0˚47'14.63"W)
thornycroft S / N / W / E	Basingstoke, Hampshire; A340 / A3010 / B3400 (51˚15'56.29"N, 1˚ 6'28.65"W)
owrnmr S / W	Crowthorne, Berkshire; B3430 (51˚23'4.62"N, 0˚47'35.01"W)
bassett S / SW	Southampton, Hampshire; A33 / A35 (50˚56'26.73"N, 1˚24'25.16"W)
hilllane W	Southampton, Hampshire; A35 / Hill Lane (50˚56’3.25”N, 1˚25’8.57”W)

From the selected sites, the relevant dependent and independent variables were then measured using methods with sufficient accuracy, requiring the minimum of resources and no disruption to live traffic.

3.4 Measurement of geometric variables

Geometric variables were either measured off high resolution aerial or satellite photographs (Microsoft Corporation, 2013; Google, 2012) or up-to-date site plans imported into AutoCAD (Autodesk Inc., 2012), or otherwise provided by TRL Limited in the case for the owrnmr roundabout. Scaling of the aerial/satellite photographs to overlaid Ordnance Survey digital mapping (Ordnance Survey, 2012) showed that any distortion caused by the camera perspective was not an issue, as the mapped features matched in position and size after appropriate uniform scaling. One reason for the use of aerial photographs, aside from their relative accessibility, was that as-built survey plans may no longer reflect their current geometry of the roundabouts due to their age and changes in lane markings or layout. In contrast, the available aerial/satellite imagery was more recent based on their known dates; their currency was also confirmed through judicious detailed comparisons with on-site photographs in terms of the condition and positions of roadway markings, surfaces and appurtenances, supplemented by historical street-level and aerial imagery (Google, 2012) to identify any changes in roundabout layouts.

Measurement with aerial/satellite photographs was particularly suited to variables such as entry radius or entry angles as they depend on accurate determination of kerb-line or lane-marking alignments. On-site surveys for such measurements would require adequate safe access to the roadway if they were to produce major improvements in accuracy; this was not a practical alternative due to the potential traffic disruption.

Figure 3-2 Example Google Earth imagery used for measurements (Infoterra Ltd & Bluesky, 2013).

3.5 Measurement of entry capacity and flow variables

Hypothesised explanatory variables which fluctuate temporally (e.g. circulating flows) should be measured during periods of queuing which reflect capacity conditions, so that their relationships with capacity can be determined. However, depending on the RFC and the level of platooning of arriving vehicles (caused by upstream traffic signals), roundabout entries may not have extensive and uninterrupted queues even during peak traffic periods, and this limits the amount of capacity data which could be extracted from them. To maximise the data yield for empirical analysis and therefore improve the robustness of the statistical analyses, it was necessary to investigate methods to extract as much usable capacity flow data from each site as possible. This was also important to yield useful flow data from entries which were not heavily saturated but had desired geometric or other properties to be included in the sample for better empirical modelling.

3.5.1 Defining periods of capacity conditions

At-capacity or beyond-capacity conditions at a roundabout are typically manifested by long queues of considerable duration (Burtenshaw, 2012, p.291). However, using criteria based on such conditions greatly reduces the yield of available data from roundabouts with lower RFC's and transient queuing. Alternatively, by considering the behaviour of the vehicles near the give-way line in congested conditions, the entry flow from a roundabout lane could reasonably be assumed to reflect its capacity if: 1) there is uninterrupted demand in the sense that at least one vehicle is always at or near the give-way line ready to enter any available gap in the circulating flow, and 2) entering drivers are motivated enough to accept their minimum safe gap available in the circulating flow. These two criteria were used to define periods where capacity data could be extracted, and are elaborated below:

3.5.1.1 Uninterrupted demand

Uninterrupted demand at the give-way line is a necessary prerequisite for maximum entry flow, as any interruptions could result in a potentially usable gap in the circulation being unused. In principle, uninterrupted demand can occur without queuing, such as when a platoon of vehicles enters into a large gap at minimum headways without stopping, but non-queued entry flows have not been found to exceed those from queued conditions (Barnard *et al.*, 1995, p.10; Rodegerdts *et al.*, 2006, p.J-10).

This study therefore assumed that uninterrupted demand occurred as long as there was a queue of at least one vehicle present at the give-way line, provided the next vehicle arrived soon or near enough to be able to accept any available safe gap or lag in the circulation immediately after the queued vehicle departs, but at a safe minimum following distance. This was also consistent with the ITE Manual of Transportation Engineering Studies (Schroeder *et al.*, 2010, p.99) classification of queued vehicles as those which are stopped or nearly stopped and travelling at less than about 5 km/h or within 2-3 vehicle lengths from the vehicle in front. One advantage of using this criterion was that any significant gaps left by queue-splitting or lane-changing in flared entries (as discussed in section 2.1.2) could be excluded as they effectively interrupt the demand at the give-way line; this thus enabled direct comparison of measured lane capacities from flared and unflared entries and better reflected the capacities limited by the give-way mechanism.

In practice, without video-based automated vehicle tracking technologies or similar to determine instantaneous speeds and/or temporal and spatial headways, a degree of subjectivity is involved in assessing whether the following vehicle was close enough to maintain the continuity of demand. This was based not just on the time or distance headway between the two entering vehicles, but also their absolute and relative speeds and accelerations or decelerations, as well as the position of forthcoming circulation gaps. However, if most of the observed flows came from clearly continuous queues with little lane-changing, the impact of errors arising from this subjectivity would likely be small across the resulting dataset.

3.5.1.2 Driver motivation for gap acceptance

When demand flow reaches or exceeds capacity, there are likely to be sustained queues forming, resulting in increased queuing delays for arriving drivers and longer queues. Larger queued delays have previously been found to reduce critical gap (Polus *et al.*, 2005; Polus *et al.*, 2003; Teply *et al.*, 1997; Ashworth and Bottom, 1977), most likely by increasing driver motivation to accept smaller gaps down to a minimum limited by acceptable collision risk. If there are no counteracting changes in follow-on headway, this suggests that queues of longer length and duration could lead to greater entry flows and capacity.

However, other studies have not been as conclusive on the effects of delays. For example, Teply *et al.* (1997) found that the minimum accepted gap significantly increased with the waiting time at the front of the queue up to about 30-40 seconds before decreasing thereafter, and suggested that there could be other motivating factors aside from driver impatience, including the possible need for drivers to observe and learn the priority flow characteristics. Rodegerdts et al. (2007, p.52) did not find any significant correlation between queue duration and gap parameters despite a wide range of queue durations observed. Furthermore, long queues may not necessarily be associated with large delays when queue discharge rates are high at low circulating flows.

Determining queued delays requires monitoring the arrival time of vehicles at the back of the queue, but this was not possible with the available resources in this study. The minimum queue-length criteria of 3.5.1.1 was thus used to determine the existence of at-capacity conditions, given that the drivers could be sufficiently motivated as long as there was at least one vehicle queued or approaching behind them (Teply *et al.*, 1997). To check whether the effect of larger delays could increase capacity flows, the corresponding overall duration of the queue for each flow data point was also recorded as a variable to be investigated, as it could be regarded as a proxy for average queued delay in that measurement period.

Another consideration for driver motivation is that there should not be any obstructions to vehicle entry caused by queues forming within the circulation downstream of the entry. This may occur when exits are blocked or queues spill back from downstream links. As the entry flow is inhibited (unless entering vehicles can pass through gaps in the standing queues), the resulting observed entry flows do not reflect those of good operational conditions for which the roundabout should be designed to achieve (i.e. free-flow circulation), and thus do not reflect expected at-capacity conditions.

3.5.2 Time intervals for capacity flow measurement

The two criteria above were used to decide on the start and end times of periods of continuous saturated demand for each lane, during which capacity flows could be recorded. It was then necessary to divide these varying time periods into smaller intervals to maximise the number of capacity data points for an adequate statistical analysis, taking into account the variability of the data resulting from microscopic differences in driver gap-acceptance decisions and other factors. Also, given that saturated entry demand typically coincides with a prevailing range of circulating flows due to peak-hour demand and turning patterns, one key advantage of small time intervals is that it also enables a wider range of circulating flows (the key explanatory variable for capacity) to be captured; this was important to determine its relationship to entry capacity.

Although Marstrand (1988) argued that the use of very short time intervals may not reflect longer-term sustainable conditions due to inherent fluctuations in both entry and circulating flows, the average of the measurements from 1-minute time intervals has been found through simulation to be representative of flows of longer duration (Brilon and Stuwe, 1993; Brilon and Stuwe, 1992). Previous studies have used time intervals for roundabout capacity measurement ranging from 30 seconds (Leemann and Santel, 2009; Semmens *et al.*, 1980), 1 minute (Wei *et al.*, 2011; Tenekeci *et al.*, 2010; Rodegerdts *et al.*, 2006; Lindenmann, 2006; Al-Masaeid and Faddah, 1997; Polus and Shmueli, 1997; Brilon and Stuwe, 1993; Stuwe, 1991; Semmens, 1988; Glen *et al.*, 1978; Kimber and Semmens, 1977; Marlow and Blackmore, 1973; Sawers and Blackmore, 1973), to 5 minutes or more (Louah, 1992: CETE West/Girabase; Marstrand, 1988; Ashworth and Laurence, 1978; Philbrick, 1974). The LR942 model (Kimber, 1980) used a combination of 1 to 5 minute intervals since it aggregated the data from several different studies, while SETRA (Louah, 1988) used variable time intervals based on queue duration.

To select the most appropriate method for flow data collection in this research, a small study investigating options based on variable time intervals and fixed time intervals for flow measurement was performed. The objective was to develop a resource-efficient method which allows more capacity flow data to be collected for any given site while producing reasonably stable data which could be analysed through exploratory data analyses; the latter being important to investigate functional relationships between the hypothesised explanatory variables and entry capacity.

3.5.2.1 Variable time intervals

Flows averaged over variable time intervals were investigated using a sample of detailed headway data from the saturated middle lane of the west entry of Thornycroft roundabout in Basingstoke. The times of all circulating vehicles passing the upstream end of the give-way line, and entering vehicles crossing the give-way line, were recorded. Gaps accepted by at least one entering vehicle were identified. The time interval based on 8 or 12 circulating vehicle headways surrounding the accepted gap (illustrated in Figure 3-3) was used to calculate the applicable circulating flow rate corresponding to the time when the gap was accepted; the accepted gap itself was either included or excluded. Likewise, the entry flows were calculated based on the reciprocal of one entry headway or the average over three entry headways. These flows based on variable time intervals were also compared with flows averaged over fixed whole-minute intervals.

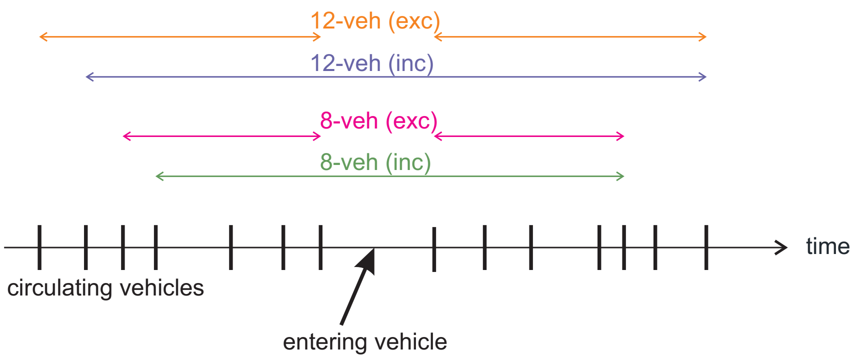


Figure 3-3 Circulating headways used to calculate headway-based average circulating flows for a given entering vehicle.

The number of data points increased when they were calculated based on the above method, although their variability increased greatly with smaller time intervals (Figure 3-4 and Figure 3-5). The R^2 values from the best-fit lines based on the variable time intervals were all less than 0.08, which was much poorer compared to that for the minute-based data points (R^2=0.7). In particular, Figure 3-5 shows that with single entry headways, the entry flow values tended to be near dichotomous, due to multiple vehicles entering the same gap with very low headways between them, separated by long pauses due to the lack of acceptable gaps in the high circulating flow. Averaging the entry flows over three entering vehicles produced less variability, as did increasing the number of circulating headways used; these then allowed the trend in the data to be observed more clearly when compared to the benchmark minute-based flows. Including the accepted gap in the average Q_c calculations also provided a better match with the minute-based flows, particularly with larger flows.

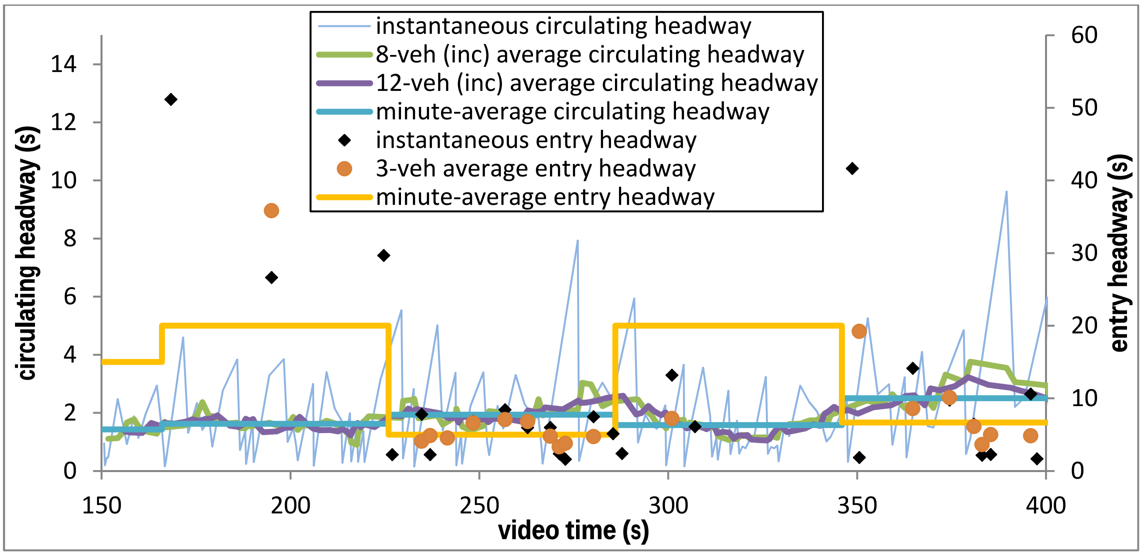


Figure 3-4 Comparison of entry and circulating flows from different measurement methods, showing temporal fluctuations.

However, notwithstanding the relatively small sample of data used, there appeared to be large differences in the linear least-squares lines. It was also more difficult to identify the relationship between entry capacity and circulating flow compared to the minute-based points.

Part of this may be attributed to the problem of autocorrelation between the flow data points when the accepted gaps are close together, since the included circulating headways used to calculate the flow will overlap for successive entering vehicles. This could lead to difficulties with the regression analyses required to determine the relationship between the entry and circulating flows. Alternatively, entering vehicles with overlapping time intervals could be excluded, but this could greatly reduce the available dataset and result in no major advantage over fixed time intervals.

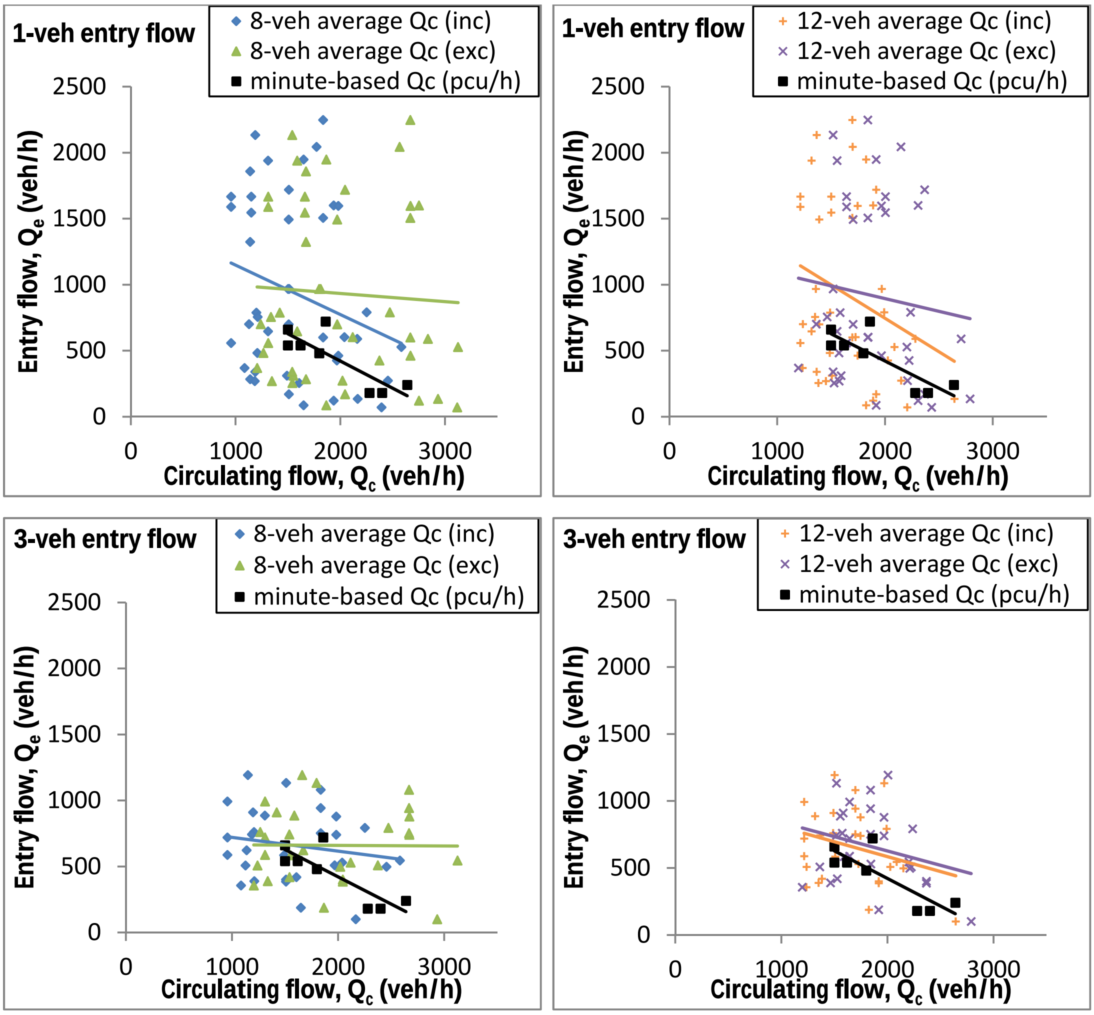


Figure 3-5 Comparison of capacity lines using circulating flows averaged over 8 (left) and 12 (right) circulating headways, and entry flows based on single entry headways (top) or three headways (bottom).

Another issue is illustrated in Figure 3-4, where the entry headways were typically much greater than the circulating headways due to the high circulating flows. This meant that the overall time intervals over which each of the entry and circulating flow data were averaged could be quite different. For example, with Q_c=1800 veh/h and Q_e=400 veh/h, the corresponding 12-vehicle circulating headways and 3-vehicle entry headways would on average be around 24 seconds and 27 seconds respectively. However, if Q_c=600 veh/h and Q_e=1200 veh/h, these would change to 72 and 9 seconds respectively. Given the transient fluctuations in headways, the large mismatch in time periods is likely to result in a very low correlation between the entry and circulating flows, as the gap acceptance decision of a single vehicle will likely depend only on the period when it is near or at the give-way line, and not on the circulating vehicles arriving 30 seconds before or after. While this issue could be avoided by adjusting the number of vehicle headways used based on the size of the flows, this introduces additional complexity into the flow calculation process.

These issues, in addition to the need for more resource-intensive measurements of individual vehicle headways, suggest that a much simpler approach of using smaller fixed time intervals is preferable, particularly given the relatively weak relationships observed between circulating and entry flows measured over variable intervals.

3.5.2.2 Fixed time intervals

Given the difficulties presented by the use of variable headways above, it was decided that fixed time intervals for flow counts should be investigated further to determine an optimal size of time interval. More data points can be obtained with smaller time intervals but at the cost of additional variability; very small intervals (e.g. 10 seconds or less) could result in near-dichotomous data points such as those seen in the top left of Figure 3-5 which could be difficult to interpret meaningfully through scatterplots. While 1-minute intervals have been commonly used in practice, it was decided to investigate the merits of using smaller 30-second time intervals for measurements.

At several selected roundabout entries, flows were enumerated from 30-second intervals which had continuous demand. Corresponding 1-minute flows were calculated by merging two consecutive intervals with continuous queues. The occurrence of isolated or residual queues lasting between 30 and 60 seconds meant that the number of 30-second data points was more than double the 1-minute data points (Figure 3-6). The smaller time intervals also yielded data points across a wider circulating flow range (Figure 3-7), albeit with greater granularity when converted to per-hour units.

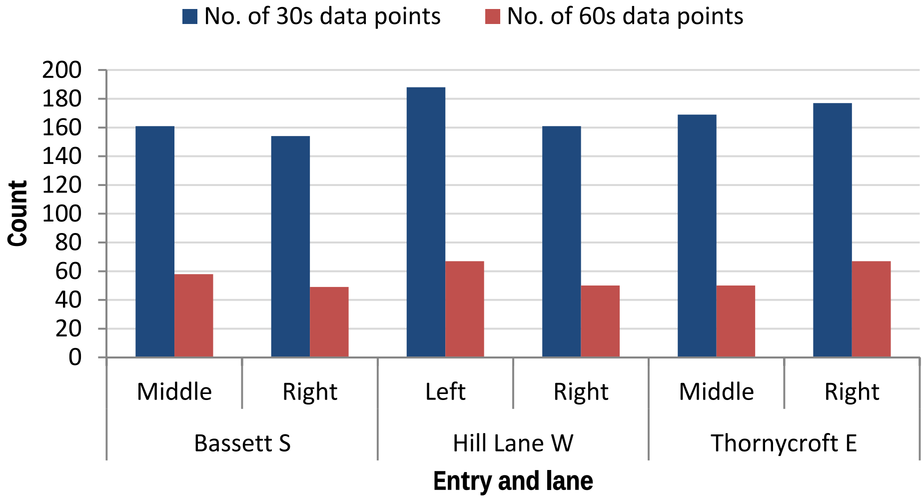


Figure 3-6 Comparison of 30- and 60-second data point yields from 6 lanes at three roundabout entries.

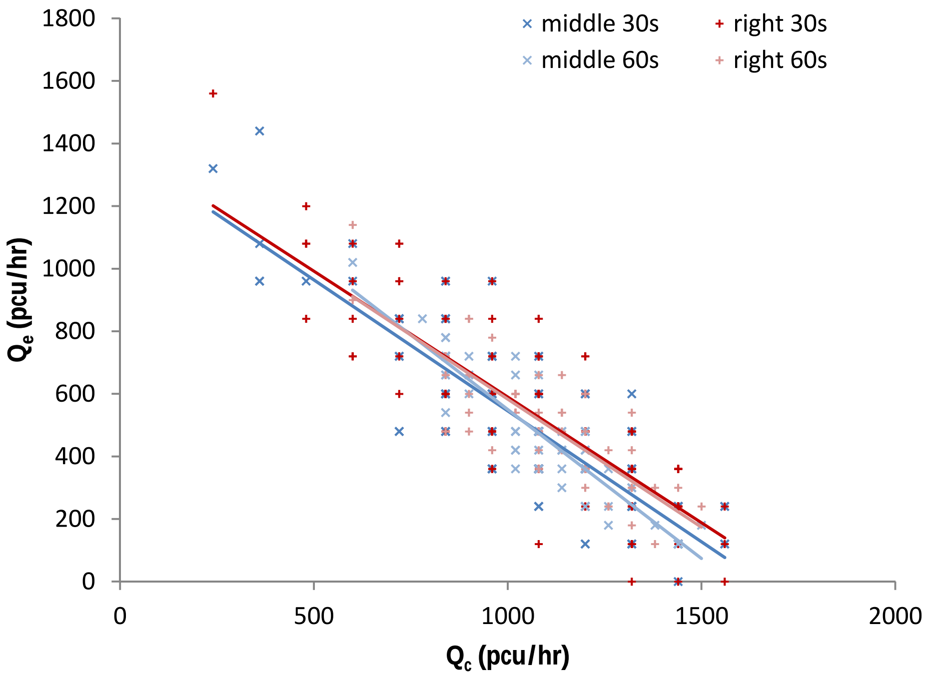


Figure 3-7 Comparison of 30- and 60-second data points for Bassett south entry.

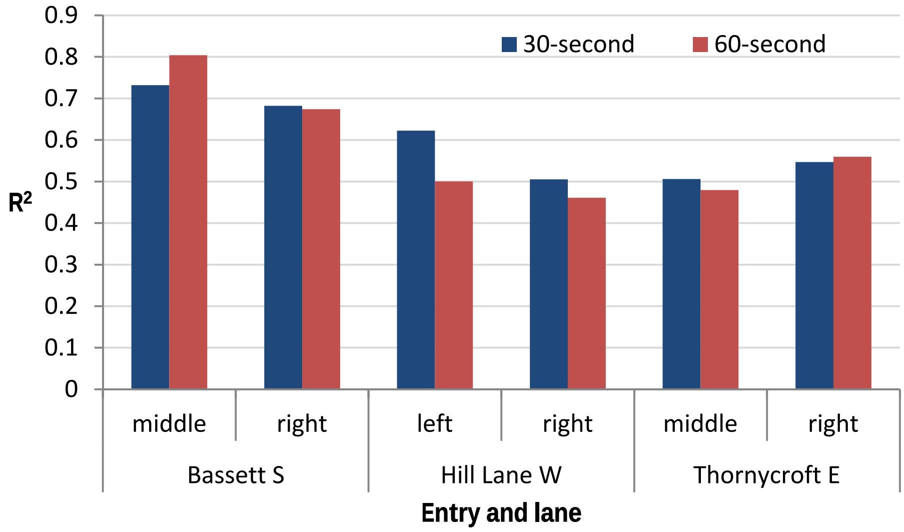


Figure 3-8 R^2 values from linear least-squares lines with 30- or 60-second measurement intervals.

There were generally little differences in the resulting capacity lines, and the R^2 fits were not consistently better with either time interval (Figure 3-8). These findings were consistent with Semmens et al. (1980, p.19) who compared 30-second intervals (including isolated saturated flows) and 2-minute intervals, and found that there were no systematic differences in the regressions. This suggested that 30-second measurement time intervals could be acceptable alternatives to 1-minute data points to extract as much capacity flow data as possible from a given site.

However, isolated 30-second flow periods are likely to be associated with smaller queued delays; as discussed in section 3.5.1.2, this could also reflect lower driver motivation for gap acceptance, and the flows could thus be less representative of at-capacity conditions. In addition, the larger scatter of the data points made scatterplots more difficult to interpret, while much greater resources was required for data enumeration. These potential issues meant that this study used one-minute intervals; this was also later found to be sufficient to achieve the required sample size of data points from the surveyed sites (as discussed in section 3.5.4).

3.5.3 Final flow measurement method

Having finalised the capacity condition criteria and time intervals, it was then possible to begin the full flow data collection. To measure entry, circulating and exiting flows from the selected roundabouts and entries, high-definition digital videos were discreetly recorded during weekday peak hour periods. The choice of morning or afternoon peak period for surveying a selected entry depended on the congestion patterns identified during the desktop-based reconnaissance. Typically, around 1.5 hours of footage could be recorded in each session, starting at either around 7.30 am or 4.15 pm and stopping when either post-peak traffic queues or daylight had subsided considerably. Noting that several entries only had short, transient periods of queueing rather than long uninterrupted queues throughout the session, it was sometimes necessary to repeat the video recording on more than one day to obtain more capacity data points (Appendix A). The videos were recorded from raised vantage points or areas well away from traffic in compliance with the University's policies on Health and Safety and Research Ethics. From careful planning and reconnaissance using Google Street View (Google Inc., 2013), it was sometimes possible to position a camera to capture two or more roundabout entries simultaneously, with the help of a wide-angle lens.

The videos were then played back at controlled speeds on a desktop computer with VLC media player (VideoLAN, 2013) or Windows Movie Maker (Microsoft Corporation, 2012). In the first pass, the start and end times of saturated demand at the give-way line for each lane (based on the criteria of section 3.5.1) were recorded manually using a VBA macro in Microsoft Excel (Microsoft Corporation, 2010) developed by the author. These periods of the video were then divided into precise consecutive one-minute or half-minute time segments, each of which was then played back a second time. In each time segment, the number of light and heavy vehicles (using either the rear of the vehicles as reference points) crossing the corresponding positions illustrated in Figure 3-9 were counted, again using the VBA macro. The vehicle counts in each interval were then converted into passenger car units (pcu) per hour, where light vehicles were assumed to be 1 pcu, while heavy vehicles with more than 4 wheels were regarded as 2 pcu. This approach is consistent with previous roundabout studies (Transportation Research Board, 2007, table 44; Semmens, 1988; Kimber, 1980; Glen *et al.*, 1978), which also found that the modelled capacities were generally insensitive to rounding of the pcu factors to these values. In any case, there was insufficient data for a more detailed investigation of pcu factors, such as that conducted by Lee (2014).

This process of enumerating from recorded videos enabled flows to be accurately and efficiently recorded with minimal on-site survey personnel and equipment, as well as allowing quality control checks on the enumerated data.

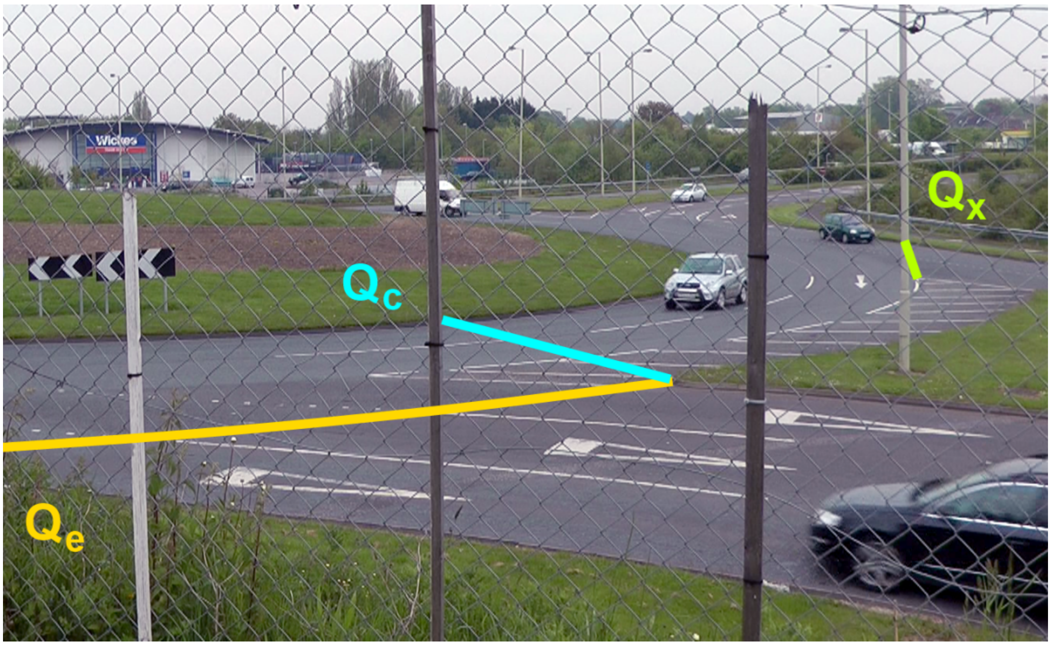


Figure 3-9 Measurement positions for entry (Q_e), circulating (Q_c) and exiting (Q_x) flows from typical video screenshot.

3.5.4 Sample size requirements

Given the finite resources available for data collection and analyses, there was a need to estimate the minimum total amount of data necessary from each roundabout entry and the whole sample for the analyses.

Smaller time intervals for measurement result in higher variability of the measured flows, so the sample had to be large enough to detect statistically significant relationships. The required sample size also depended on the desired statistical power and the acceptable level of prediction error, as well as the variability of the data. In this case, a simple power analysis was used to estimate the required sample size; by assuming an 80% power (i.e. 20% probability of Type II error), 5% significance level, 10 predictors and very small effect sizes (i.e. ΔR^2 of 1%), the minimum sample size for the linear multiple regression calculated using a sample power analysis software (Faul *et al.*, 2007) was estimated to be around 1600.

In addition to the overall sample size, a minimum number of data points was required from each lane to provide some idea of its capacity relationship as well as ensure that its characteristics were adequately represented in the sample. A few sites were therefore surveyed more than once to obtain enough flow data from them across the circulating flow range. The data from different sessions were merged together, as tests on the slopes and intercepts did not find significant differences in the Q_e,Q_c capacity lines from different survey periods in similar weather (example shown in Figure 3-10). Although this may also be due to the limited sample size in each session, there was no evidence that the data from different sessions could not be combined together for the analyses.

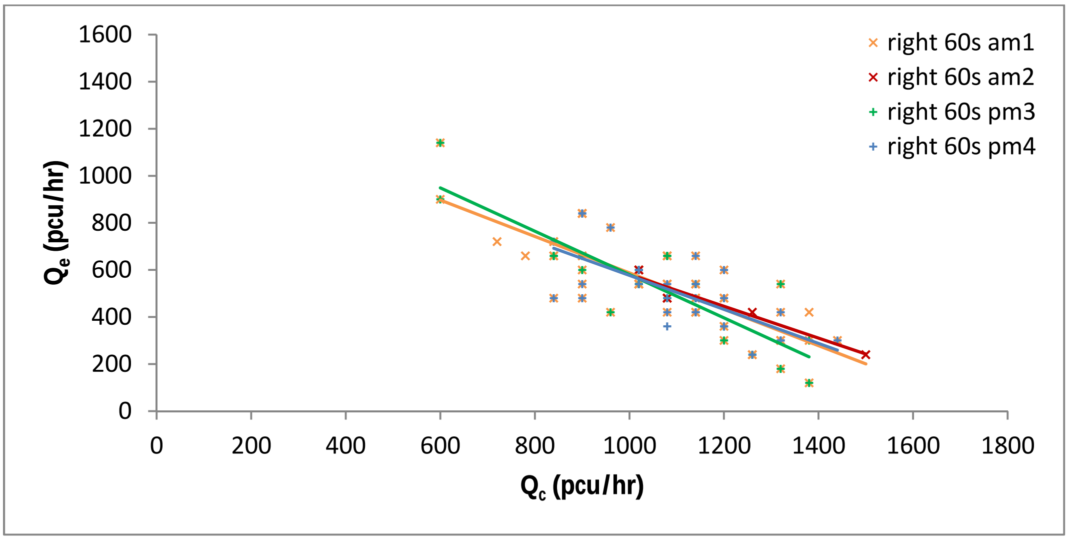


Figure 3-10 Comparison of data points and best-fit lines for Bassett South entry right lane from 4 different sessions.

3.6 Dataset characteristics

The surveys took place from May 2012 to February 2013 (Appendix A), with significant support from TRL Limited for the field recording of the videos. In total, nearly 2600 minutes of raw video footage were recorded, which after processing yielded 1753 one-minute flow data points from 19 entries at 10 roundabouts (Table 3-1), covering 35 different entry lanes. 193 data points did not include exit flows due to recording limitations, so these were excluded list-wise from the analyses where necessary. The range of geometric and flow characteristics of the dataset are summarised in Table 3-2, and further detailed in Appendix B.

Table 3-2 Range of variables observed

Variable	Units	Minimum	Mean	Maximum
Entry flow, Q_e	pcu/h	0	667	1920
Circulating flow, Q_c	pcu/h	0	1266	2880
Exiting flow, Q_x	pcu/h	0	958	2460
Inscribed circle diameter, D	m	31.0	68.1	100.2
Lane width 10 m upstream, W_L	m	2.0	3.2	4.2
Entry radius, r	m	20	74 (exc. r= ∞)	∞
Entry angle, ϕ	°	6.6	26.3	54.2
Circulation width, W_C	m	6.7	8.4	11.6
Entry-exit separation, d_{sep}	m	13.8	39.7	95.7
Distance to previous entry, d_{upe}	m	20.7	55.5	117.5
Approach lane width, V	m	2.6	3.3	3.9
Entry width, E	m	2.7	3.6	5.2
Effective flare length, l' (for flared only)	m	3.1	11.8	53.1
Minimum queue duration, t_q	minutes	1	20.5	85

Apart from one single-lane entry, all the sites had two or three entry lanes, although many had at least one lane where minute-long capacity flows did not occur due either to the lack of demand or entry starvation due to queues in adjacent lanes; these lanes were thus omitted as their capacities could not be measured using the methodology described in section 3.5.3.

Capacity entry flows are plotted against the corresponding circulating flows in Figure 3-11 for each of the sites (data from individual lanes were combined). Given that the overlapping of multiple data points which could make identification of underlying trends in the data more difficult, scatterplotsmoothing local regression (loess) lines were plotted in SPSS (IBM Corporation, 2012b). These were least-squares regression lines which were iteratively calculated at each abscissa by assigning neighbourhood weights to data points located within a vertical slice of a certain width, with more weight assigned to points nearer the centre of the slice (Cleveland, 1994).

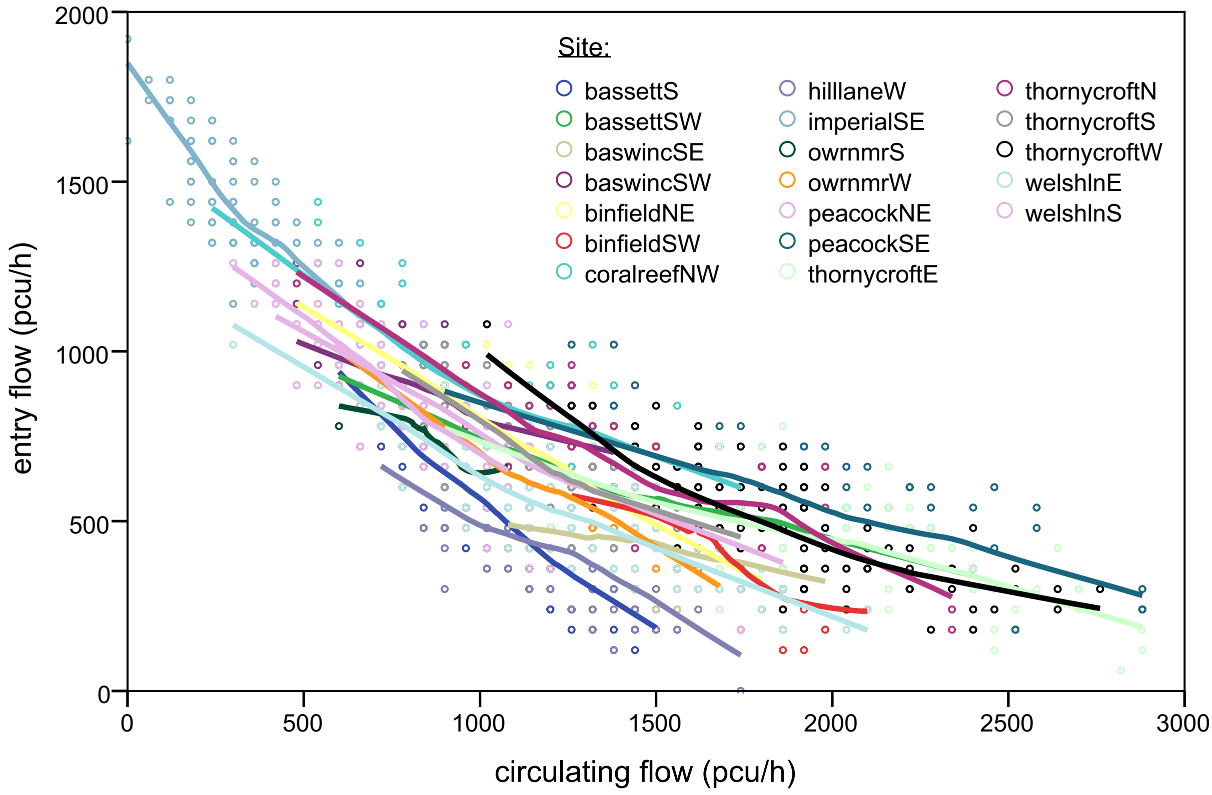


Figure 3-11 At-capacity lane entry flows from surveyed entries, with local regression lines.

There appears to be a clear non-linear trend in the overall aggregated data. However, there was typically limited range of observed circulating flows within individual sites, as this depended on the prevailing origin-destination patterns at the roundabout during the peak hour periods. This meant that a non-linear relationship is less evident within individual sites.

A few sites had significantly steeper slopes compared to others with a similar circulating range, while there were also differences in entry flow 'intercept' among those with similar slopes. Within individual sites, there was little evidence of heteroscedasticity across the circulating flow range, although this may have been masked by the limited number of data points at low and/or high circulating flows.

While scatterplots of entry capacity against each of the independent variables showed a clear strong relationship with circulating flow (Figure 3-12), the relationships with other variables were less evident due to the variability of the minute-based entry flows, the overlapping effects of multiple independent variables on entry capacity, and the correlations between independent variables (Table 3-3). The flow data variability could be reduced with the use of longer measurement time intervals (e.g. 2 minutes or more), but this will likely be at the expense of a smaller range of circulating flows and other flow variables.

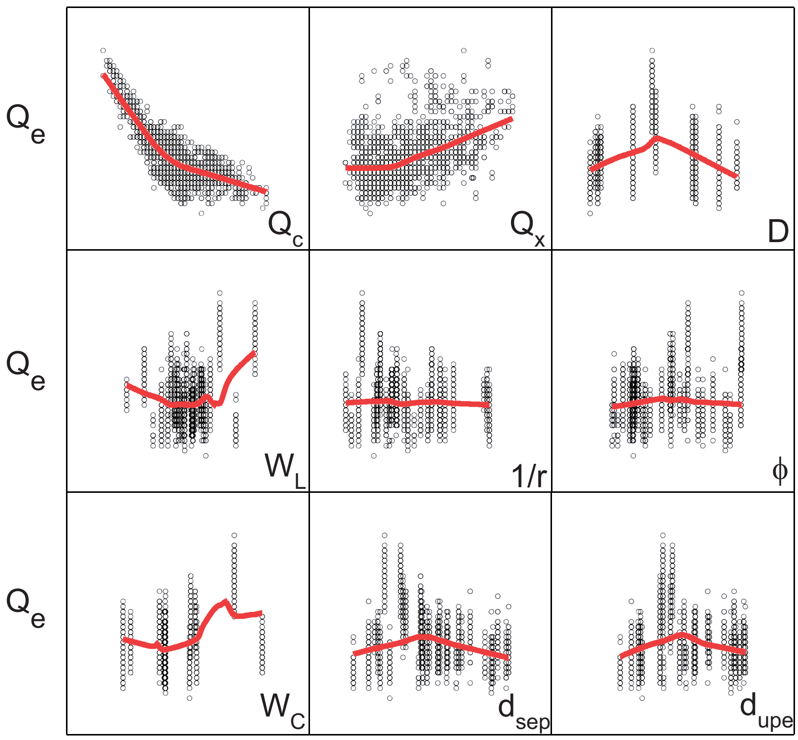


Figure 3-12 The relationships between entry capacity and each of the predictor variables (loess lines shown).

Table 3-3 Pearson correlations between variables where ** denotes significant at 0.01 level (two-tailed)

	Q_e	Q_c	Q_x	D	W_L	1/r	ϕ	W_C	d_{sep}	d_{upe}
Q_e	1	-.768**	.452**	-.011	.223**	-.138**	.131**	.297**	-.246**	-.143**
Q_c		1	-.350**	.340**	-.102**	.161**	-.019	-.247**	.461**	.379**
Q_x			1	.083**	.043	-.125**	-.182**	.169**	-.009	-.163**
D				1	.124**	.111**	.016	-.434**	.762**	.803**
W_L					1	-.279**	.227**	.135**	-.065**	-.039
1/r						1	-.337**	-.632**	.033	.010
ϕ							1	.257**	-.129**	.165**
W_C								1	-.219**	-.206**
d_{sep}									1	.892**
d_{upe}										1

Observations of vehicle behaviour at the roundabout entries during the surveys reaffirmed some of the practical limitations of capacity modelling using gap acceptance methods. In particular, defining the exact time of arrival of a vehicle at the give-way line based on its position or speed could be fairly arbitrary; vehicles were often seen to start accelerating well before arriving at the give-way line, so that they could intercept and merge into an upcoming gap or lag in the circulation. Furthermore, their momentum appeared to allow them to enter smaller gaps or lags than would have been required were they to accelerate from a stationary position at the give-way line.

A number of circulating vehicles also visibly slowed down or curtailed their acceleration to avoid colliding with entering vehicles, particularly at smaller roundabouts with slower circulating vehicles; this confirmed that either deliberate or erroneous gap or lag acceptance was a relatively common phenomenon. Several entering vehicles also visibly hesitated until oncoming vehicles were seen to be exiting rather than circulating, particularly at smaller roundabouts. These observations have potentially major implications for the determination of the critical gap, which typically relies on assumptions of homogeneity and consistency across the driver population and ignore any impact of exiting vehicles. There are also implications for the design of microscopic simulation models, given that the observed interactions between vehicles appeared to be far less passive than might have been suggested by simple priority rules; nevertheless, the observed behaviours could provide useful information to assess microscopic simulation visual outputs.

3.7 Discussion of sample limitations

As shown in Table 3-2, a reasonably large range for each of the variables was obtained despite the inability to obtain a consistently large number of data points from every site. The sampling aimed to achieve as wide a distribution of the predictor variables as possible with the available resources, but there were practical considerations which limited the database developed. There could thus be several potential implications for the follow-up statistical analyses based on the data.

A wide distribution of roundabout sizes was desired given that the existing literature suggested that size may be one of the more important variables affecting capacity, but just over 20% of the data points in the database were from roundabouts with $D<40$ m and 35% from roundabouts with $D>81$ m. This could potentially bias any resulting empirical model in favour of medium to large roundabouts, although very small multilane roundabouts may not be as common for future designs due to the difficulty of satisfying safe entry path deflection criteria (Transportation Research Board, 2010b; Department for Transport, 2007b) with smaller islands.

Also, practical considerations meant that 84% of the data points came from dry weather, with the remainder generally in light rain conditions rather than in heavy rain. The relatively low number of wet-weather data points may affect the significance of the wet weather in the subsequent analyses.

All the sites had circulating carriageways which could accommodate 2 lanes upstream of the subject entry (even though the circulating flow in some sites were predominantly concentrated on one lane); it is possible that the resulting model could thus be biased against single-lane compact roundabouts or those with 3 or more circulating lanes (although unsignalised versions of the latter are likely to be rare). These issues may restrict the range of the roundabouts which any resulting empirical model could be applied to, as it was not possible to explicitly determine how the number of circulating lanes could affect entry capacity.

Given that the variables of d_{sep} and d_{upe} were likely to share a major common component of their variation, it was important to collect data from a range of roundabouts which did not have the typical orthogonal four-arm layout; however, the sample could only include 6 entries to which the previous upstream arm which was not approximately perpendicular. Whilst this minority may be reflective of the wider population of roundabouts, this could also result in issues with multicollinearity in the regression analyses. A similar problem could arise from the relatively high correlation between several of the other variables (Table 3-3), which reflects the limited variation of the geometries of the available sites.

On-site observations of the sampled roundabout entries showed that entering vehicles typically gave-way to all circulating vehicles regardless of entry lane position, consistent with the findings of Troutbeck (1990). However, this may not be the case for other roundabout entries where the first downstream exit is much further and vehicles on the inner circulating lane do not change lanes until they exit; vehicles may be more likely to enter from the nearside entry lane (hence increasing its entry capacity) if they are certain that they do not obstruct any oncoming circulating vehicles on the inner lane from leaving the roundabout. This strongly suggested that the characteristics of the conflicting flow upstream of the entry were likely to be more important than downstream in the weaving area.

The limited resources for surveying meant that the locations of the surveyed roundabouts in this study were restricted to Hampshire and Berkshire. To account for possible regional variations in capacity arising from differences in driver behaviour – for example, for mini-roundabouts, capacity was found to be significantly higher at larger circulating flows in London (Barnard and Hall, 1997) – the transferability of the model to roundabouts from other regions should be investigated, but this was beyond the scope of this study.

3.8 Chapter conclusions

This chapter has discussed the design of sampling and collection of field data to be used for empirical studies into capacity. It was found that practical limitations constrained the possible number of hypothesised variables which could be investigated empirically, but despite this, the majority of the most important ones were identified from the literature and included in this study.

An empirical modelling approach based on capacity flow measurements in the field was chosen because it was likely to be less susceptible to uncertainties arising from the modelling assumptions and practical data-collection difficulties inherent in gap acceptance methods. Valuable on-site observations of vehicle behaviour during the data collection – particularly the interaction between entering, circulating and exiting vehicles – reaffirmed the decision to use flows for empirical modelling, rather than a headway-based modelling approach based on idealised driver behaviour such as no priority-sharing and no influence by exiting vehicles.

However, the need for a sufficient range of data for each of the predictor variables for statistical analyses meant that the sample and data collection process had to be carefully designed. Survey costs were a major constraint, and also limited the location of the roundabouts. However, these costs were minimised through the use of freely-available online resources for desktop-based reconnaissance and digital video recording. To maximise the amount of capacity data extracted from the survey sessions, several methods of capacity flow measurement were investigated, and it was found that measurement using one-minute counts was found to be the best compromise between resource requirements and data variability, although half-minute counts could be an acceptable alternative if a greater observed flow range was needed.

There was greater difficulty in achieving a wider range of geometric variables in the database, as eligible sites not just had to have sufficient queued conditions for capacity flow measurement, but also the required variability in geometric characteristics. The limitations of the sampling method and data collection thus meant that there could be potential issues with determining the effect of several variables in follow-up statistical analyses presented in the next chapter.

Chapter 4: Evaluation of existing models and development of new models

This chapter presents the results of an assessment of current capacity models using the collected data described in the previous chapter, before discussing the development of new empirical models based on the same data. Statistical regression and neural network modelling were used to assess the impact of variables and factors, so the analyses and results are described and discussed. Issues requiring further investigation have been identified, particularly the influence of two less commonly used predictor variables which could help improve capacity estimates. The bulk of this chapter has undergone the peer review process and has been published as a journal paper: YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (in press) Models of Roundabout Lane Capacity, Journal of Transportation Engineering, ASCE, doi: 10.1061/(ASCE)TE.1943-5436.0000773.

4.1 Evaluation of existing models

Given the inconsistencies of the various international models highlighted in section 2.2, the first step performed with the collected data was to assess the ability of existing capacity models to predict lane capacity for a typical set of roundabouts. This could then identify whether there was a need to develop improved models, and – given their disparate model specifications – also enable a better understanding of how existing models could be improved upon.

The observed capacity flows were thus compared with those predicted by the uncalibrated international models using the relevant inputs from the actual dataset. The models and the assumptions required to calculate lane capacities were:

- LR942 model (Kimber, 1980) with three calculation methods which were either partially or wholly adopted from the ARCADY User Guide (Burtenshaw, 2012):
  - nominal lane capacity based on individual lane geometry
  - apportioning approach capacity equally among the number of lanes
  - apportioning approach capacity according to the ratio of nominal lane capacity intercepts.

- HCM 2010 model (Transportation Research Board, 2010a), where the middle lane of 3-lane entries was assumed to be equivalent to the nearside lane of a 2-lane entry. The exception to this was the Peacock Farm roundabout (peacock in Table 3-1) where vehicles in the middle entry lane merged with the inner circulating lane instead of the outer circulating lane.
- Brilon-Wu model (Wu, 2001), with default gap and headway parameters
- Bovy-Tan model (Simon, 1991), assuming single-lane entry and lane-specific separation distance values
- Girabase model (Guichet, 1997), where approach capacity is divided by the number of lanes
- SIDRA model (Akcelik & Associates Pty Ltd, 2011), with no adjustment factors for origin-destination or environment, and each lane assumed to be dominant (since lane demand flows could not be recorded).

The model-predicted capacities were plotted against the observed capacities in Figure 4-1, and the root mean square errors calculated.

The accuracy of the predictions may have been affected by several simplifying assumptions necessary due to the limited types of field data available for comparison; this was particularly pertinent to the SIDRA model with its more extensive traffic inputs, although it should be noted that some of the assumptions (e.g. dominant vs. sub-dominant lane) resulted in quite small differences to its predictions. Nevertheless, it is observed in Figure 4-1 that the French Girabase model has the best fit of the models above, despite some systematic over-prediction at higher entry flows (corresponding to lower circulating flows).

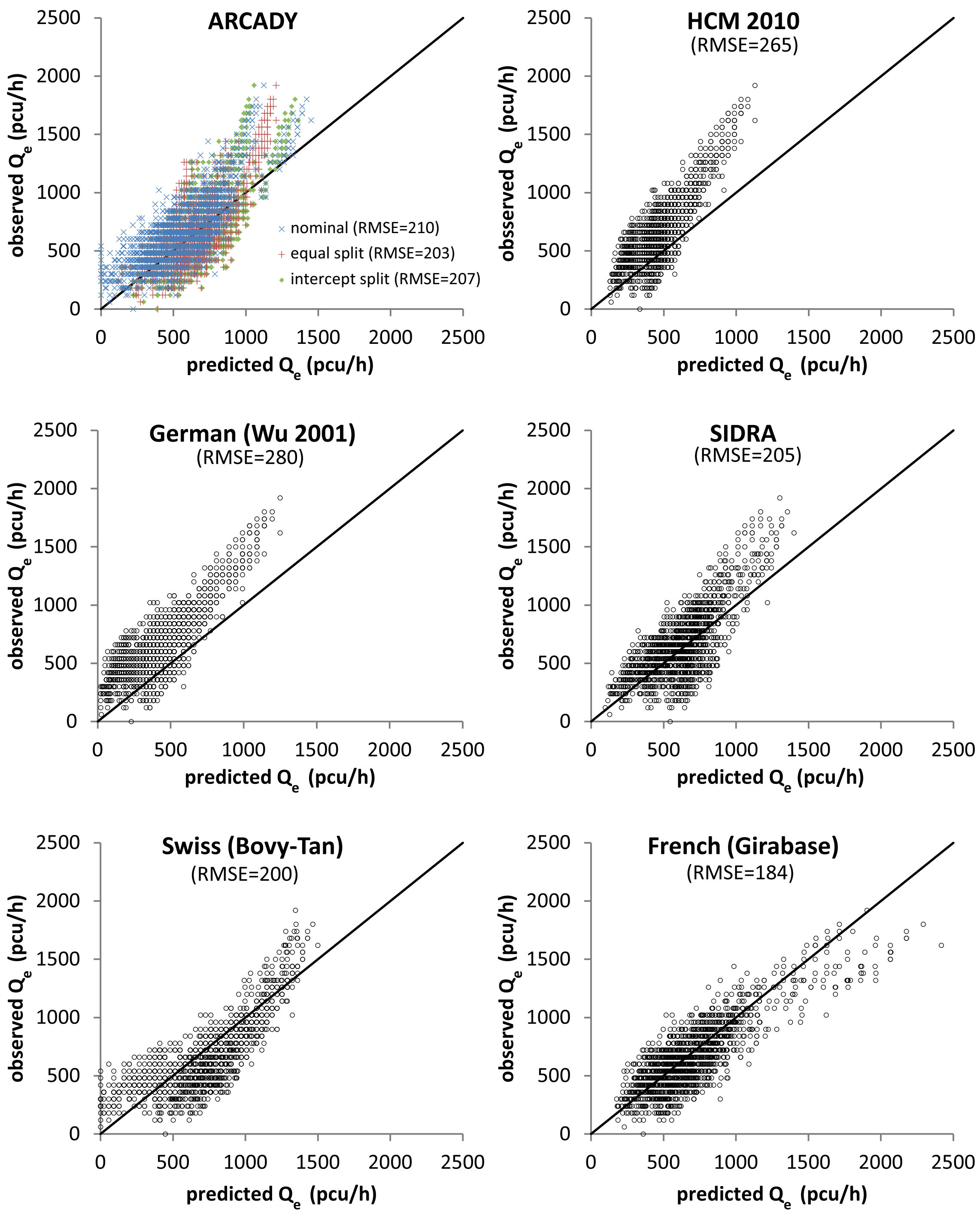


Figure 4-1 Comparison of uncalibrated international models applied to the observed dataset, with root mean square errors (RMSE) shown in pcu/h units.

Figure 4-2 shows that the LR942 nominal lane capacity method produces steeper slopes compared to the other two LR942 methods in which the whole-approach capacity was apportioned. This was likely because in the original LR942 model based on whole-approach entry width, small single-lane entry widths – similar to those of individual lanes – would likely have been associated with smaller roundabouts with fewer circulation lanes and crucially, less flaring effects (as described in section 2.1.2). The nominal method provided better fits to sites with lower circulating flows, although the overall fits was slightly worse compared to the other two methods.

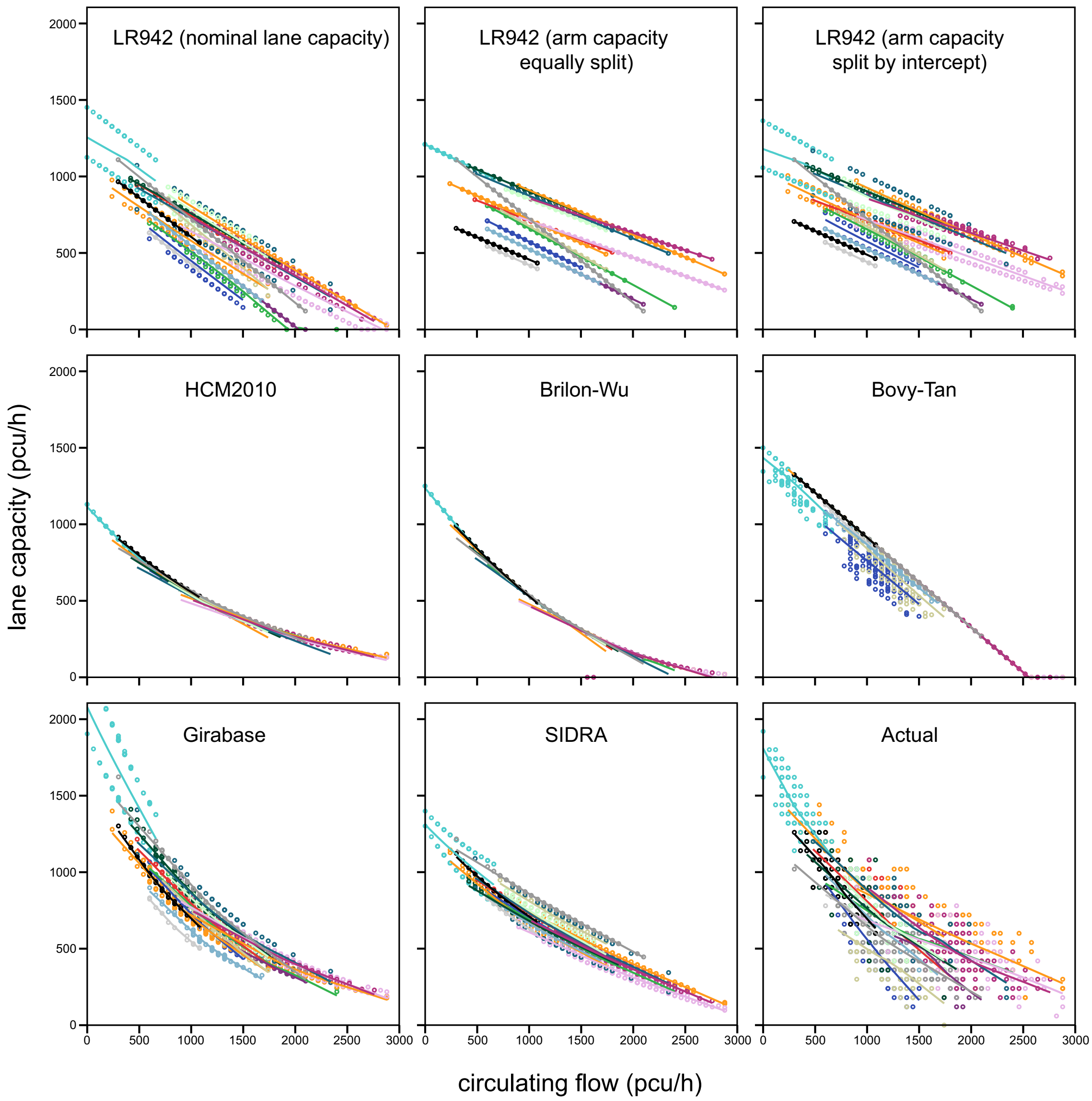


Figure 4-2 Predicted entry capacities against circulating flow for existing models and actual data, with site-specific loess lines.

Comparison of the model-predicted capacities and the site-specific observed capacities in Figure 4-2 shows that the insensitivity of models such as the HCM 2010 and the Brilon-Wu to geometry may account for their relatively poor ability to predict capacities for different sites. These two models were based on gap acceptance modelling, as was SIDRA; however, the main difference between them and SIDRA was that the latter included statistically significant relationships between geometry and headway parameters, enabling it to better account for site-to-site variability and produce a better fit to the overall dataset.

Similarly, the functional forms of the other models restricted their predictive ability for individual sites. For example, the Bovy-Tan model is linear with respect to circulation flow, with only differences in intercept to account for site-to-site variation; however, the actual capacity curves clearly differ in both 'slopes' and 'intercepts' (Figure 4-2). The empirical models such as the Girabase and LR942 appear to be able to accommodate greater site-to-site variability given their sensitivity to geometric variables, but the LR942 generally under-predicted capacity at lower circulating flows. In contrast, the Girabase model, with its exponential model form, predicted better at low circulating flows. However, its reduced site-to-site variability at higher circulating flows is a reflection of its exponential model form in which geometric or flow variables are applied either multiplicatively or within the exponent term – this reduction in variability was not observed in the actual capacity data.

Some of the predictive errors could possibly be attributed to differences in behaviour between different driver or vehicle populations. For example, the HCM2010 and Brilon-Wu models were calibrated using data from U.S. and German drivers respectively, who may generally have had less experience with roundabouts compared to say, U.K. drivers; similarly, anecdotal evidence suggests that vehicles in the U.S. are on average larger than those in the U.K.. This could explain their under-prediction of capacity evident in Figure 4-1 and Figure 4-2. Also, given the age of some of the models (for example, the LR942 model was developed 35 years ago), there may also have been changes in driving behaviour, vehicle characteristics or roundabouts designs, resulting in differences between modelled and current capacities. However, in most of the models, the systematic trend of greater under-prediction of lane capacity at higher entry flows (corresponding to lower circulating flows) and the observations in Figure 4-2 suggest that there may be structural shortcomings affecting their accuracy when applied to this new dataset.

These capacity prediction errors could be reduced by using relevant site-specific measurements such as critical gaps or recommended calibration methods such as intercept corrections or 'environment factors'. However, such procedures would not reflect how these models could be applied to new roundabouts in the absence of local information, and it is not clear how further changes in geometry affect parameters which have been calibrated (Yap *et al.*, 2013). Thus, the results here show that existing models may not be sufficient to accurately predict lane entry capacity, and that further model development is required.

4.2 Empirical model development

The literature review and the assessment of current models suggest that there is a need to identify the factors and variables which significantly affect roundabout capacity, and their relationships with entry capacity. Towards this, it is necessary to develop a model which relates observed at-capacity entry flows to hypothesised explanatory variables suggested by prior research and listed in section 3.1.

4.2.1 Regression modelling

Using the available data, new empirical models were developed using statistical methods such as multiple linear or nonlinear regression; Further information on these methods can be found in many statistical textbooks (e.g. Kutner et al. 2005 and Cohen et al. 2003), but they essentially involved estimating parameters in hypothesized relationships between independent explanatory variables and dependent variable through least-squares minimization of errors (residuals). The importance of each explanatory variable was determined by evaluating the statistical significance of its coefficient, and the improvement in model fit resulting from its inclusion; this also applied to any two-way interactions between explanatory variables where the impact of one variable depended on another. The form of the hypothesized relationship between each independent variable and capacity was typically assumed to be linear by default, unless theory or scatterplots suggested otherwise.

Previous empirical studies (Transportation Research Board, 2007; Polus and Shmueli, 1997; Brilon and Stuwe, 1993; Louah, 1992; Semmens, 1988; Kimber, 1980; Glen *et al.*, 1978; Kimber and Semmens, 1977) variously used linear or negative exponential relationships between Q_e and Q_c. To investigate the best regression form for the analyses here, smaller 30-second measurement time intervals were used in several roundabouts, with observations in both morning and afternoon peak periods to widen the range of circulating flows (data points from different periods did not show any statistically-significant differences in linear slopes and intercepts, and so were combined together; likewise, there were no statistical differences between 30-second and one-minute regression lines). As shown by the example in Figure 4-3, these did not conclusively show that nonlinear relationships were better than linear for individual roundabouts, despite the wider range of circulating flows. However, the slopes of the linear model for large and grade-separated roundabouts had previously been found to depend on prevailing circulating flows (Semmens, 1988), while Figure 3-11 suggests that a nonlinear relationship could be more appropriate in the absence of advance knowledge of the applicable circulating flow range for a proposed roundabout.

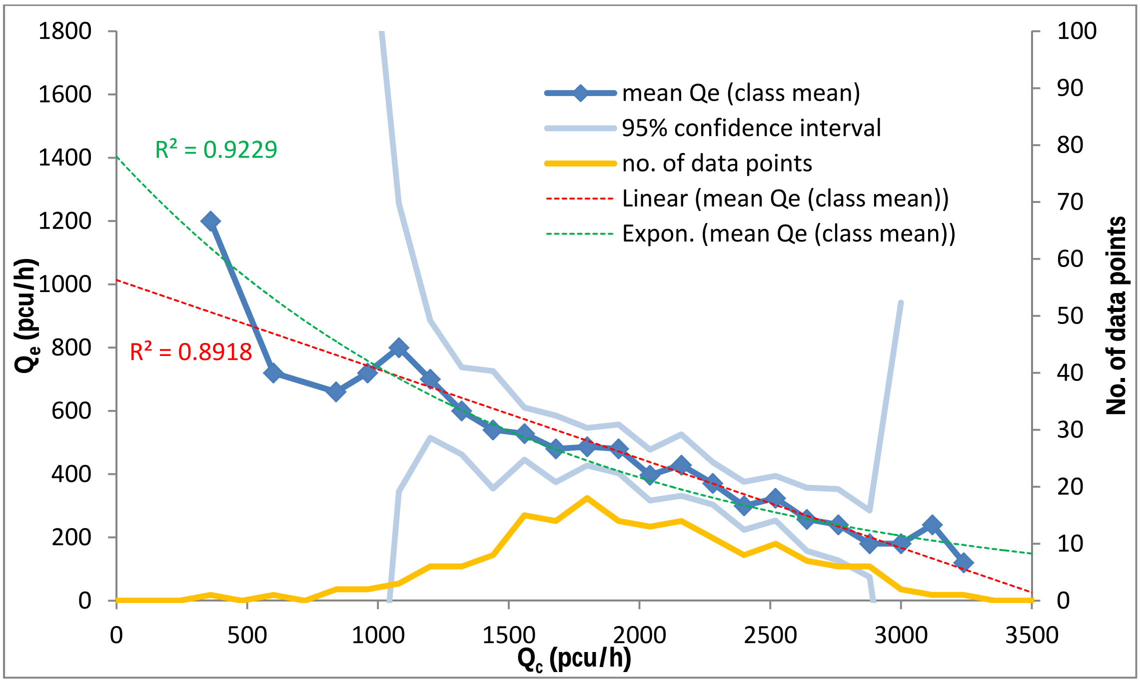


Figure 4-3 Class mean lane entry flows from the middle lane of the east entry of Thornycroft roundabout, based on 30-second measurement time intervals.

Both linear-in-Q_c and exponential-in-Q_c forms were therefore investigated in the regression analyses. The 'slopes' and/or 'intercepts' appeared to be site-specific, so the tested models were linear with input-dependent intercept and gradient (Q_e=A+BQ_c), or negative exponential with constant or input-dependent asymptote, 'slope' and/or 'intercept' ($Q_e=Ae^{BQ_c}+C$); A, B and/or C was $m+\Sigma p_i X_i$ where X_i were included explanatory variables, m and p_i were parameters to be determined through least-squares regression. Quadratic or piecewise linear spline functions in Q_c were also investigated but they suggested counterintuitive behaviour within the range of observed data, such as increasing capacity at very high circulating flows.

Based on the scatterplots of regression residuals and previous studies (Troutbeck, 1989; Marstrand, 1988), a nonlinear relationship between Q_e and D was tested using D^2 or two-way D interaction terms. There was little consistent evidence to suggest the form of the relationship between Q_e and the other explanatory variables so simple linear additive effects were assumed, complemented by checks on the regression assumptions through residual scatterplots.

The regression models assumed additive (as opposed to multiplicative), homoscedastic (i.e. uniform variance) and normally-distributed errors (ε). This was because part of the observed entry flow variability was likely to be from random driver and vehicle characteristics which were not explicitly included in the model; there was no evidence from the scatterplots to show that these errors were proportionate to Q_e or that the assumptions were inappropriate.

In contrast to linear regression with closed-form solutions for model coefficients, the nonlinear exponential model required least-squares error minimization using numerical methods. Statistical tests in the nonlinear model assumed that the sample was large enough for least-squares coefficients to be normally-distributed and almost unbiased; the appropriateness of this was verified by comparing confidence interval estimates with those from bootstrapping[3].

The size of the sample meant that a large number of parameters were significant at the 5% level, despite the number of input variables considered and their

[3] an alternative to statistical inference based on assumptions such as normal distribution, bootstrapping computes the standard error of the parameter using the observed distribution of mean values of a large number of sub-samples obtained through random and repeated resampling (with replacement) from the main sample; this is further explained in Kutner et al. 2005

relatively weak effects. There was limited information from existing studies regarding the relative importance of the explanatory variables apart from circulating flow and diameter. Hence, a series of regressions using backwards variable elimination starting from all (and various subsets of) the variables in Table 3-2 was used to estimate the relative contributions of individual variables, followed by hierarchical forward variable selection (where the main variable and two-way interaction terms were entered manually, with the order of entry based partly on the improvement in adjusted R^2) to develop more parsimonious final models (example shown in Figure 4-4).

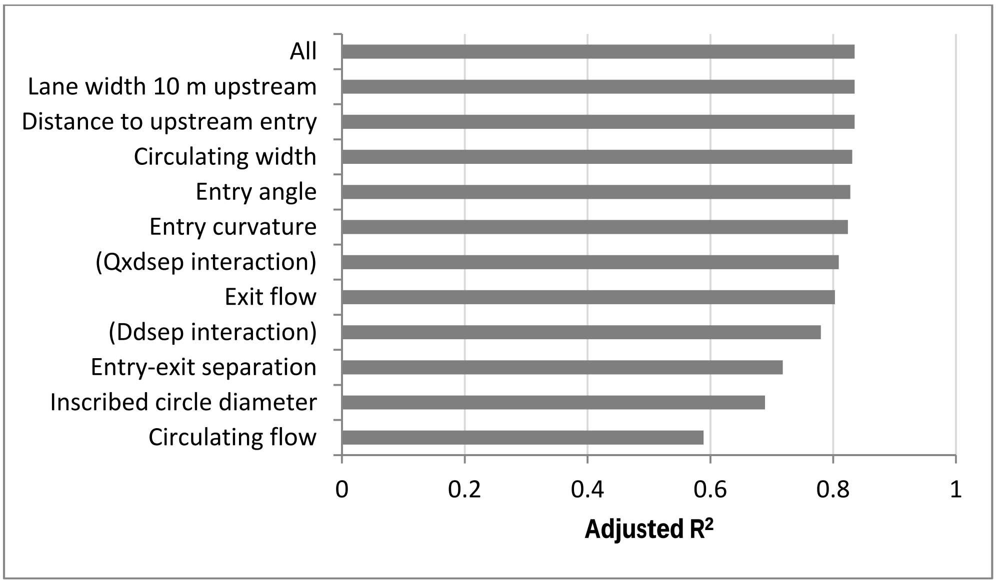


Figure 4-4 Adjusted R^2 values of sub-models created with the hierarchical addition of variables and their interactions (starting with circulating flow), for Model 1.

All the regression (and the neural networks discussed in the following section) analyses were performed in SPSS (IBM Corporation, 2012b). Over 210 regression models were investigated, and although these were not exhaustive given the number of possible combinations of variables and their interactions, the models below represent the best combinations based on the heuristic process outlined earlier:

Model 1: Multiple linear regression (R^2=0.825, adjusted R^2=0.824, root-mean-square-error RMSE=126.5 pcu/h):

$$Q_e = 1113 + 15.9\ D - 5.99\ d_{sep} - 0.243\ D \cdot d_{sep} + 0.0103\ Q_x - 7801\ (1/r) + 0.00435\ Q_x \cdot d_{sep}$$
$$+ [-0.952 - 0.00313\ D + 0.0153\ d_{sep} - 0.000108\ Q_x + 7.51\ (1/r)]\ Q_c$$

Model 2: Nonlinear exponential regression model with additive error and variable asymptote (R^2=0.839, adj. R^2=0.838, RMSE=121.3 pcu/h):

$$Q_e = -771 + 8.01\ D + 7.00\ d_{sep} - 0.103\ D \cdot d_{sep} + 0.0572\ Q_x + 2088\ (1/r) + 40.7\ W_C$$
$$+ 1580\ EXP(-0.00103\ Q_c)$$

Regression diagnostic tests to check on the independence and normality of the errors (e.g. Durbin-Watson statistic, regression residual scatterplots) showed that the regression assumptions for the two models above were not violated. While there was some degree of collinearity between several of the independent variables (arising especially from two-way interactions), they were not severe enough to warrant the omission of variables from the regression as they provided a useful increase in adjusted R^2.

The significant two-way interactions showed that the impact of certain variables was dependent on the value of the interacting variable. For example, the impact of d_{sep} on entry capacity depended on the value of D, as increased separation could have different impacts depending on whether the roundabout was large or small. The linear model had a greater number of significant two-way interactions, reflecting the changes in entry capacity slope with respect to circulating flow.

Table 4-1 Parameter estimates and their standard errors from regression models; all parameters are significant at the 5% level except for that marked *

	Linear model 1		Exponential model 2	
Parameter	Estimate	Std. Error	Estimate	Std. Error
Intercept	1113.168	51.096	-770.987	64.749
Q_c	-0.952	0.038	-0.001030	0.000045
D	15.907	1.011	8.011	0.449
d_{sep}	-5.988	1.458	6.997	0.963
Q_x	0.010*	0.024	0.057	0.007
1/r	-7801.14	790.916	2087.965	325.176
$D \times d_{sep}$	-0.243	0.013	-0.103	0.011
$Q_c \times D$	-0.003	0.001	-	-
$Q_c \times d_{sep}$	0.015	0.001	-	-
$Q_c \times Q_x$	0.000108	1.627E-5	-	-
$d_{sep} \times Q_x$	0.004	0.001	-	-
$Q_c \times 1/r$	7.515	0.665	-	-
W_C	-	-	40.669	5.543
multiplier constant	-	-	1580.140	26.121

Despite having only five and six traffic and geometric variables respectively, the linear and exponential models above compared favourably to models of equivalent form but including all other variables and interaction terms (those had adjusted R^2 values of 0.835 and 0.842). For the exponential model, an alternative model form which had the exiting flow Q_x as part of a conflicting flow (i.e. $Q_c+k \cdot Q_x$ or $Q_c+k \cdot d_{sep} \cdot Q_x$ in place of Q_c) did not show an improvement in model fit. Other additive-error exponential models using input-dependent ‘slopes’ and ‘intercepts’ did not improve on the model fit, while the implied complex interactions among the variables in these models were difficult to justify. Exponential models with multiplicative error terms and multiplicative variable effects [$Q_e=m_0 \cdot (\Pi X_i^{p_i}) \cdot e^{mQ_c} \cdot \varepsilon$] which could be linearly regressed via logarithmic transformation also produced poorer fits to the data. Model forms based on the LR942, Girabase, Brilon-Wu and SR45 (Troutbeck, 1989) capacity models were also tested by recalibrating their parameters for the new dataset, but these also produced poorer model fit (Table 4-2).

Table 4-2 Regression equations for existing models with Δ, a_x and t_x parameters recalibrated to new dataset.

Model form	Regression equation	Model fit statistics
LR942	$Q_e = \left[a_0 - a_1(\emptyset - 30) - a_2\left(\frac{1}{r} - 0.05\right)\right] \times \left\{a_3\left[v + \frac{e-v}{1+a_4\left(\frac{e-v}{l}\right)}\right] - a_5\left[a_6 + \frac{a_7}{1+e^{\left(\frac{D-a_8}{a_9}\right)}}\right]\left[a_{10} + a_{11}\left(v + \frac{e-v}{1+a_4\left(\frac{e-v}{l}\right)}\right)\right]Q_c\right\}$	RMSE=155 R^2=0.725
Girabase (simplified)	$Q_e = \left[a_0\left(\frac{W_L}{3.5}\right)^{a_1}\right]e^{(a_2 Q_c + a_3 Q_x)}$	RMSE=155 R^2=0.739
Brilon-Wu	$Q_e = \left(1 - \frac{\Delta Q_c}{7200}\right)^2 \frac{3600}{t_f} e^{-\frac{Q_c}{3600}\left(t_c - \frac{t_f}{2} - \Delta\right)}$	RMSE=160 R^2=0.708
Troutbeck (SR45 simplified)	$Q_e = \frac{(a_0 - a_1 Q_c)Q_c e^{-\frac{(a_0 - a_1 Q_c)Q_c}{1-\Delta Q_c}(t_c - \Delta)}}{1 - e^{-\frac{(a_0 - a_1 Q_c)Q_c}{1-\Delta Q_c}t_f}}$	RMSE=152 R^2=0.731

4.2.2 Neural network modelling

Various transportation studies (e.g. Karlaftis and Vlahogianni, 2011; Özuysal *et al.*, 2009; Dougherty, 1995) have used artificial neural networks (NN), which are an important alternative to regression models based on statistical inference for data analysis and pattern recognition in large datasets. A neural network is a mathematical model comprising a layer of input nodes and a layer of output nodes (where the numbers of nodes in each layer depend on the number or type of explanatory and dependent variables respectively), connected by at least one layer of hidden nodes. Each hidden node contains an activation function, which transforms the weighted and combined inputs from preceding layers into an output signal. The strength of the signals relayed between the connected nodes in successive layers thus depend on weights and biases whose values are optimised through learning algorithms from a set of training data. The trained system can then be used for predicting outputs from a given set of inputs – similar to how biological neural networks work.

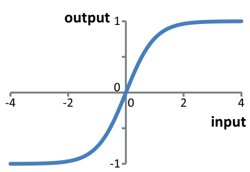
Linear regression models, with their assumption of linear relationships between dependent and explanatory variables, are analogous to a very simple NN with identity activation functions, one output and no hidden layers; the inputs are explanatory variables, the output is the dependent variable, while the coefficient and intercept parameters correspond to NN weights and biases (Kutner *et al.*, 2005 p.547). However, NN's with hidden layers and sigmoidal activation functions which are appropriately-structured and trained are able to approximate much more complex relationships between dependent and explanatory variables, including nonlinearity and interactions between explanatory variables (Kutner *et al.*, 2005 chapter 13.6; Sarle, 1994). This meant that NN modelling had a potential advantage over regression models for roundabout capacity modelling, given the unknown form of the true capacity relationships as illustrated by differences in existing capacity models (Yap *et al.*, 2013) and the difficulty of identifying relationships from exploratory scatterplots of capacity data. NN modelling was thus used here to assess the ability of the regression models developed above to represent the actual relationships between the input and capacity, given that those models had been constrained by *a priori* assumed functional relationships. NN modelling also enabled the determination of the extent to which the observed variation in the capacity could be explained by the inclusion of the selected explanatory variables, again without the constraint of assumed relationship forms.

To assess whether the regression models constrained by *a priori* functional relationships were acceptable alternatives for modelling the relationships between the input variables and Q_e, they were compared against NN's based on a simple feed-forward[4] multilayer perceptron[5] with a single hidden layer using hyperbolic tangent activation functions[6] (an example is illustrated in Figure 4-5). The number of hidden nodes was determined through progressive removal or

[4] The signals move only in one direction towards the output, as opposed to other configurations containing loops or cycles where the signal can also feed backwards to unit/s in a preceding layer.

[5] This is a type of neural network which has more than one layer (i.e. a hidden layer), as opposed to single layer perceptrons with no hidden layers.

[6] Activation functions transform an input signal into an output signal; in this case, a tanh function produces a nonlinear response to the input signal:



inclusion of hidden units based on the changes in training errors, while weights and biases were optimised through error back-propagation in which numerical methods were used to minimize the model's sum-of-squares error.

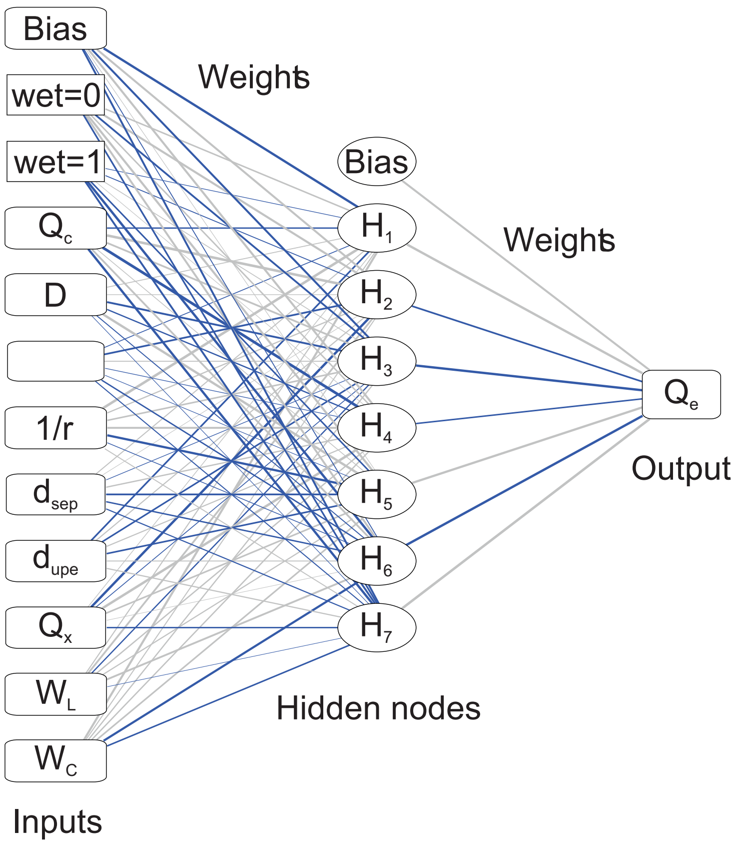


Figure 4-5 Neural network with 10 predictor variables.

To account for the stochastic nature of the NN optimisation process (IBM Corporation, 2012a, p.5), ten NN's were developed for each set of explanatory variables. It was found that NN's with all the variables included had an average R^2 of 0.877. However, as shown in Table 4-3, NN's with a subset of 4 or 5 variables including either exiting flow or entry-exit separation was sufficient to account for most of the model fit.

Table 4-3 Comparison of neural networks with best-performing variable sets.

No. of variables	Variables										Mean R^2	Mean RMSE (pcu/h)
	Q_c	D	W_C	d_{upe}	1/r	W_L	d_{sep}	ϕ	Q_x	Wet /dry		
1	✓										0.736	152.0
2	✓	✓									0.809	129.4
3	✓	✓					✓				0.848	115.3
4(a)	✓	✓	✓						✓		0.865	111.3
5(a)	✓	✓	✓	✓					✓		0.867	110.2
4(b)	✓	✓	✓				✓				0.857	112.1
5(b)	✓	✓	✓				✓		✓		0.862	112.1
All	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	0.877	106.2

4.2.3 Comparison of regression and neural network models

As shown in Figure 4-6, Figure 4-7 and Figure 4-8, the inherent flexibility of the neural network models enabled them to produce the best fits to the observed data. However, scatterplots of predicted capacity from the all-variable NN's appeared to indicate some over-fitting, as shown by inexplicable undulations in the NN loess curves for a few sites in Figure 4-7 despite a large number of data points. Hence, the linear and exponential regression models would be preferred for engineering application due to their comparable predictive ability and easier interpretation of variable effects. Although the exponential Model 2 provided marginally better overall fit, linear Model 1 was a slightly better fit for sites with steeper slopes despite slightly under-predicting at low and high circulating flows (Figure 4-6 and Figure 4-7). Hence, although the nonlinear relationship between entry capacity and circulating flow across the whole dataset could be represented by either an exponential-in-Q_c model or a linear-in-Q_c model with interactions, the latter may be less accurate at very low or very high circulating flows.

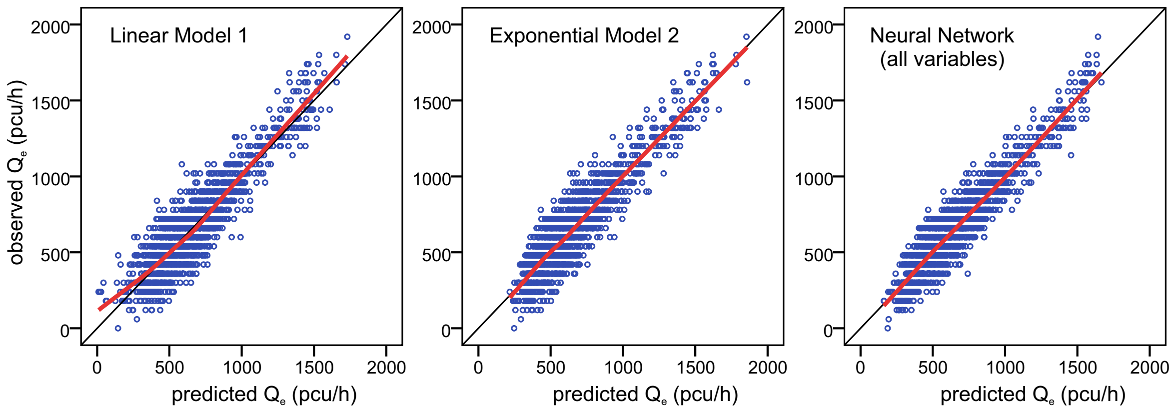


Figure 4-6 Comparison of actual against predicted capacities for the new empirical models, where red lines are loess fit lines.

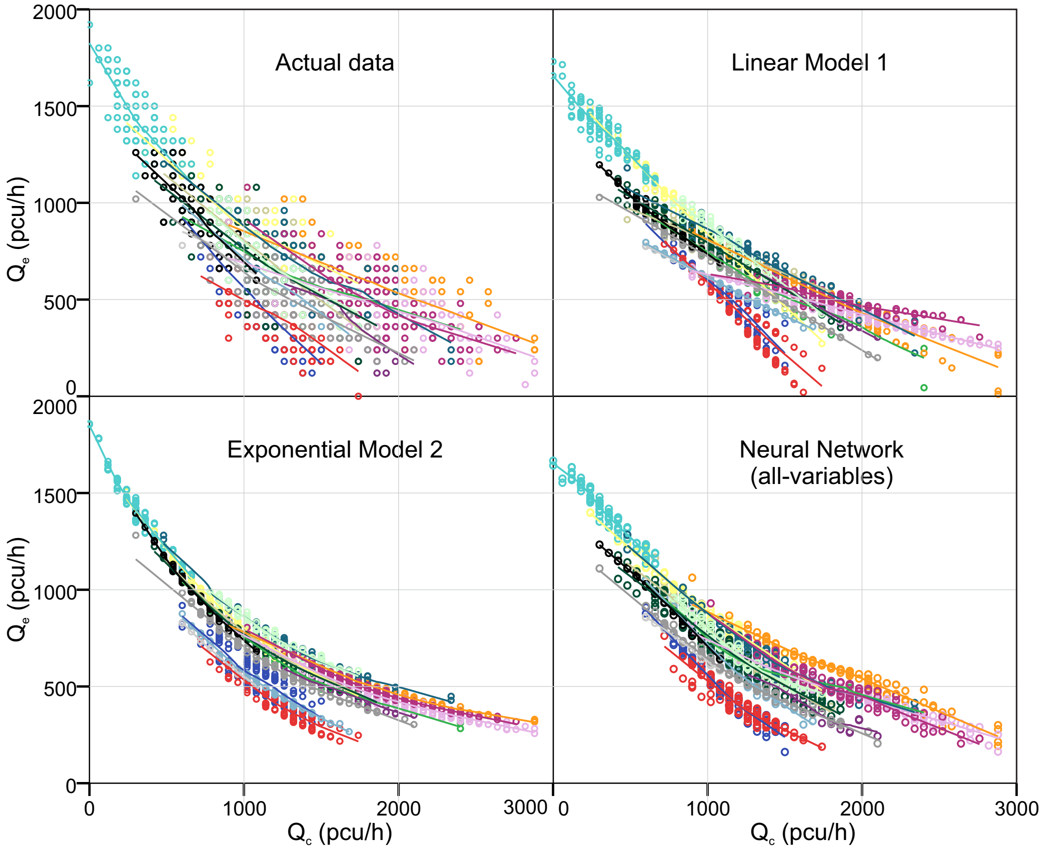


Figure 4-7 Predicted lane entry capacities of models, where colours denote sites.

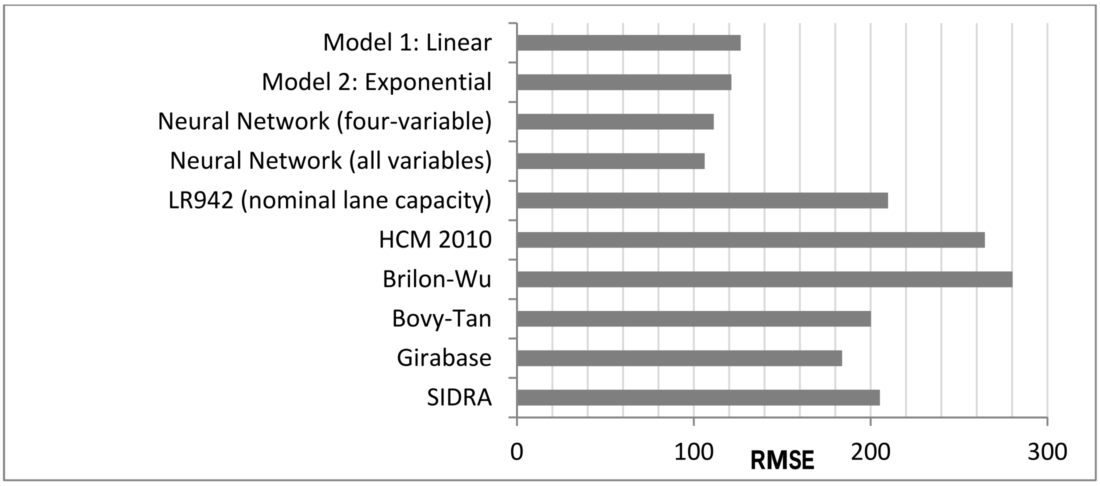


Figure 4-8 Comparison of RMSE values (pcu/h) between empirical models and international models.

Figure 4-8 shows that the RMSE of the existing capacity models in default form exceeded those of the new empirical models, by a minimum of 60 pcu/h or 50% when compared against the regression models. Although this is not unexpected given that the new models have been specifically calibrated to this dataset, the size of the errors further illustrates the limited accuracy of existing models when applied to new roundabouts without calibration, and also the potential improvement in accuracy possible with the inclusion of additional explanatory variables in an appropriate form.

The regression and neural network analyses show that the circulating flow and diameter were the most important explanatory variables for lane entry capacity. At the other end, queue duration and wet weather had insignificant impacts, although the latter may have been due to the lack of data from heavy rain conditions. Between these, separation and exiting flow appear to contribute significantly more to the fit of the models compared to other variables such as entry radius, entry angle and lane width (Table 4-4).

Table 4-4 Ranking of the explanatory variables (including interactions) by contribution to model fit, where # denotes insignificant or weak contributions to model R^2 of less than 1%.

	Variables						
	Q_c	D	d_{sep}	Q_x	1/r	W_C	ϕ, d_{upe}, W_L, wet/dry, queue duration
Linear Model 1	1	2	3	4	5	#	#
Exponential Model 2	1	2	4	3	5	6	#
Neural Networks	1	2	4	5	6	3	#

4.2.4 Effect of variables

The study's focus on lane capacity unencumbered by flare effects or fluctuations in demand may have produced cleaner data which enabled the effects of each of the variables to be better detected, compared to previous studies. Assuming all other variables were unchanged, the effect of larger diameter was to increase the lane entry capacity in both regression models, although this increase was less at higher circulating flows in Model 1. Greater circulating width significantly increased capacity in Model 2 but not in Model 1, illustrating the sensitivity of the parameter effects to the form of the assumed relationships. In contrast to SIDRA and LR942, both models suggested that greater entry curvature increased capacity (except at lower Q_c in Model 1), although the effects of both entry curvature and circulating width were quite weak compared to other variables. Variables thought to have greater impact such as entry angle and entry width (Kimber, 1980; Akcelik & Associates Pty Ltd, 2011) also appeared to have comparatively weak or insignificant effects, although it is likely that entry width would be more important for the overall capacity of flared entries compared to a single line of queuing vehicles.

The regression and neural network analyses consistently suggest that separation and exiting flow had significant and relatively important effects on lane entry capacity. During the surveys, it was observed in several roundabouts that entering drivers were not accepting available gaps or lags until oncoming conflicting vehicles were observed to be exiting rather than circulating. This would manifest in a negative impact on capacity when separation was reduced and/or exiting flows were increased, as suggested by several preceding studies (Mereszczak *et al.*, 2006; Hagring, 2001; Louah, 1992; Tan, 1991). However, both the new linear and exponential regression models above – and other existing empirical models (Guichet, 1997; Semmens, 1988) – suggest that other mechanisms may also apply. For example, larger exiting flows in the two regression models here appeared to increase capacity at low circulating flows regardless of roundabout size or separation (Figure 4-9).

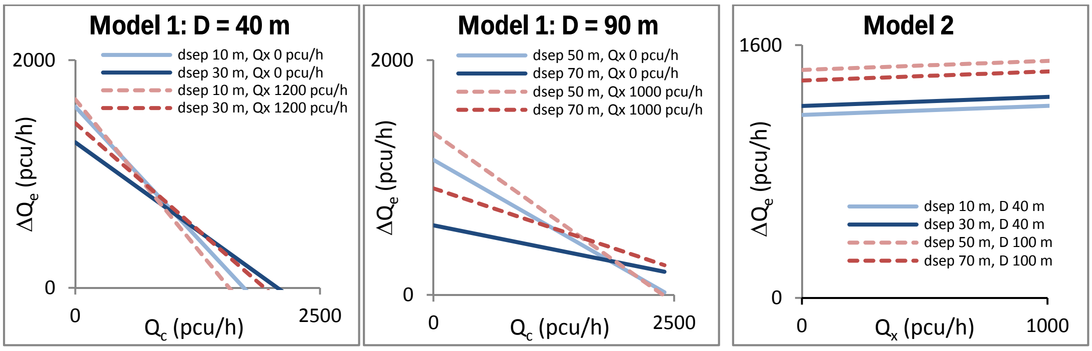


Figure 4-9 Example of impacts on entry capacity by separation distance (d_{sep}), exiting flow (Q_x), diameter (D) and circulating flow (Q_c) in the regression models, assuming all other variables were constant.

This previously-unexplained positive impact of exiting flows pointed to a major gap in our knowledge, and strongly suggested a need for further research to better understand the effects of exiting flows and separation on lane capacity, particularly in multilane roundabouts. The subsequent chapters in this thesis thus address this particular issue in further detail.

4.2.5 Caveats

Resource limitations and thus the limited sample size available for model calibration and validation mean that there are a number of caveats to the findings above. Although the chosen sample attempted to maximise the range of each of the variables, it was ultimately limited by the availability of entry lanes with measurable capacity flows, which in turn could also limit the generalizability of the findings to all roundabouts especially with other driver and vehicle populations. The statistical significance of regression parameters may have been affected by collinearity between several of the variables arising from the constraints on the geometric layout imposed by design guidelines, vehicle swept paths and geometric compatibility.

The assumed regression model forms would have constrained the apparent directions of the variable effects; although a large number of models (including several based on existing capacity models) were investigated, there is a possibility that a different model form could provide a better description of the effects of the variables on capacity. However, the variability of the flow measurements from the short time intervals did not allow the determination through exploratory data analyses of more definitive functional forms of the relationship between many variables and Q_e; there was also limited theoretical background available for this purpose. Also, the empirical models here have focussed on lane capacities by excluding the effects of flaring which could significantly reduce the usable capacity; in flared roundabout entries, additional modelling such as the Entry Lane Simulation of ARCADY / Junctions 8 (TRL Software, 2012) will be required to account for the reduction in lane entry flows caused by entry starvation due to lane choice patterns and lane queues.

4.2.6 Validation of linear and exponential models

In light of the caveats above, the validity of the models was assessed by withholding a small proportion of the full dataset for validation rather than for calibration of the models. Although the reduced calibration dataset could result in a poorer model, large systematic errors in the model predictions for an excluded test site could indicate poor transferability of the model due to its form and inputs.

In this case, data from the Coral Reef NW, Binfields NE, Thornycroft W and Bassett S entries (which comprised around 7%, 7.6%, 6.0% or 7.1% of the total data respectively) were used in turn for validation. The data from the remaining entries were used to recalibrate the parameters of the linear, exponential and all-variable neural network models; the recalibrated models were then used to predict the capacities for the selected sites and compared against the observed entry flows in Figure 4-10.

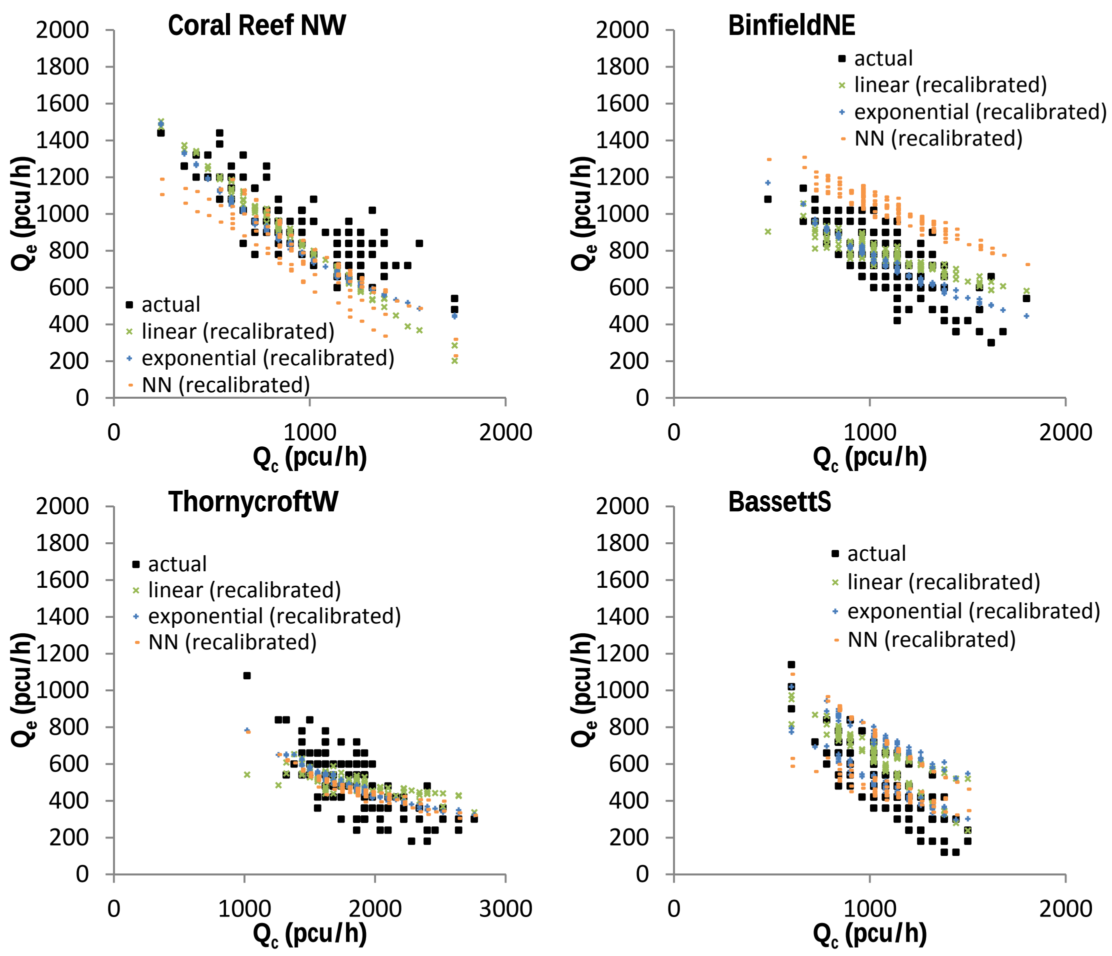


Figure 4-10 Comparison of capacities predicted by recalibrated regression models against the actual data.

In Figure 4-10, the neural network appears to be showing signs of over-fitting and poor transferability, given its relative poor predictive performance for BinfieldNE and Coral Reef NW. However, both the linear and exponential regression models appear to show relatively good validity based on the overlapping of the predicted and actual data points for the four entries, with the exponential model providing marginally better fit. For comparison, the transferability of the regression models to these four roundabouts generally appear to be as good as existing roundabout capacity models represented by the Girabase and LR942 models in Figure 4-11, with the exception perhaps of BassettS.

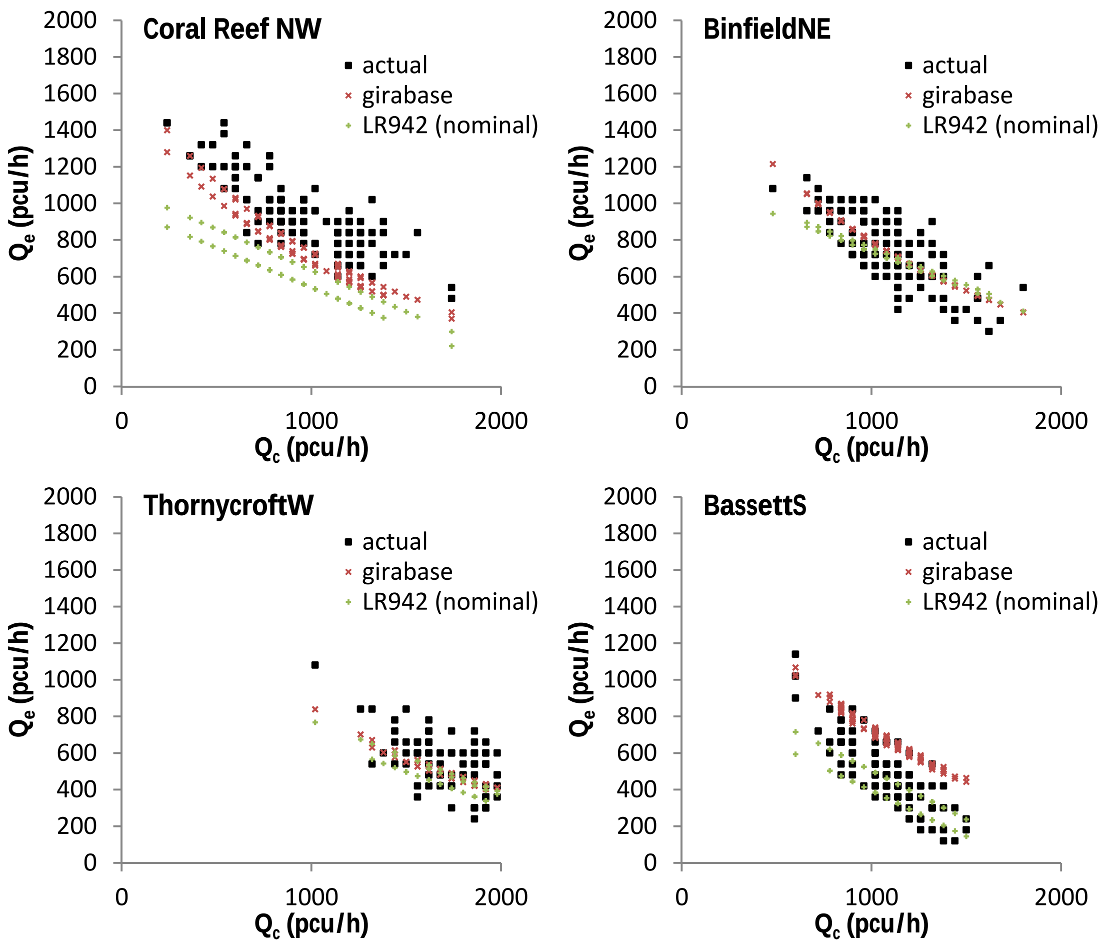


Figure 4-11 Comparison of capacities predicted by LR942 and Girabase models against the actual data.

It should be noted that the regression models here were not calibrated with the complete dataset; using the full dataset for calibration will likely improve its performance.

4.2.7 Sensitivity analyses

While the video-based data collection process and quality control checks minimised any errors in the enumerated flows, errors in the geometric measurements could arise from the limits of aerial/satellite image resolution. Sensitivity analyses were thus performed to assess the impacts of these errors on the models developed above, and therefore the robustness of the models.

As the position of longitudinal lane markings could be clearly defined in the aerial/satellite images and the lines were of standard widths (Department for Transport, 2003), it was estimated that measurement errors of more than 5% were unlikely i.e. equivalent to 15 cm for a 3 m lane width. Hence, a simple error distribution was assumed for the geometric input variables to be tested, where for the selected vitiated variable (i.e. the variable with deliberately inflated error), a randomly-chosen subset comprising one-third of the measurements was increased by 5%, another one-third was decreased by 5% and the remainder left unchanged.

Using this method, sensitivity analyses were performed on each of the significant input variables in the regression models (D, d_{sep}, 1/r and W_C) one at a time. The linear and nonlinear regression models were then recalibrated with the vitiated inputs, and the new predicted capacities recorded and plotted against those from the original model. Large sensitivities to errors would be indicated by larger deviations from the $Q_{e(original)}=Q_{e(vitiated)}$ line. For the 10-variable neural network, an additional run which simultaneously included the four vitiated variables was performed to reflect the impact of possible co-variation between the variables.

As expected, the error introduced into the vitiated variable resulted in slight reductions in R^2 values (up to 1%) of the models. As shown in Figure 4-12 and Figure 4-13, deviations from the $Q_{e(original)}=Q_{e(vitiated)}$ line for the regression models were generally larger with diameter and separation, although the exponential model was more sensitive to circulating width; these thus suggest that the accurate measurement of these variables was more important than curvature. Nevertheless, Table 4-5 suggests that the size of the capacity errors for the regression models were quite small, and were unlikely to greatly affect calculated RFC values for capacity analysis except at high circulating flows.

These deviations were not due to an unexpected increase in the variable's weight in the recalibrated model, as comparisons using the original model parameters with the vitiated variables showed fairly similar results. However, the stochastic model optimisation process meant that the deviations from the recalibrated NN with different variables were inconclusive (i.e. no clear differences in the graphs from each of the vitiated variables), so Figure 4-14 shows the comparisons with original NN without recalibration. This and Table 4-5 show how sensitive the NN's were to errors in circulating width, suggesting that the NN's could be over-fitted with excessive variation particularly attributed to the circulating width.

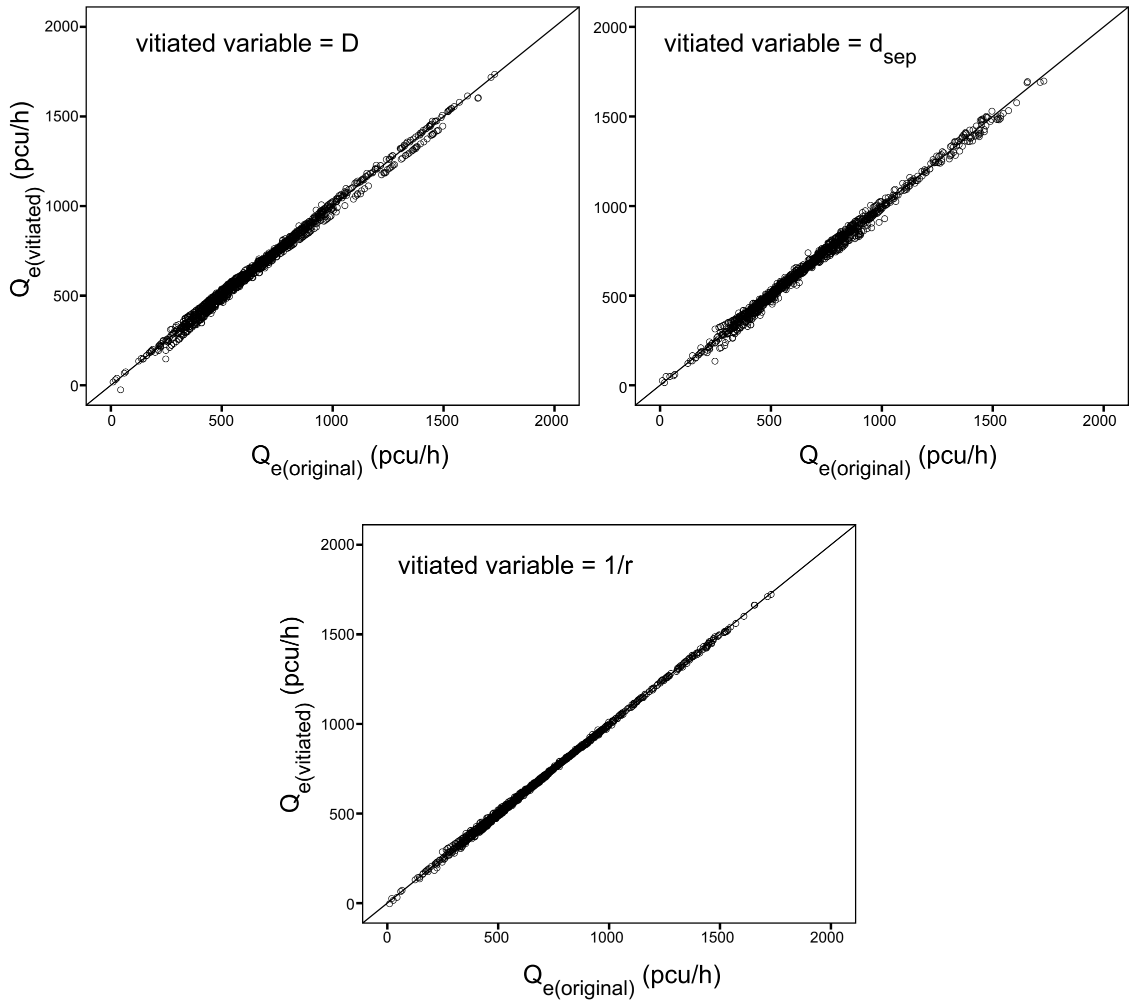


Figure 4-12   Comparison of predicted capacities from original linear model and linear model recalibrated with vitiated variables.

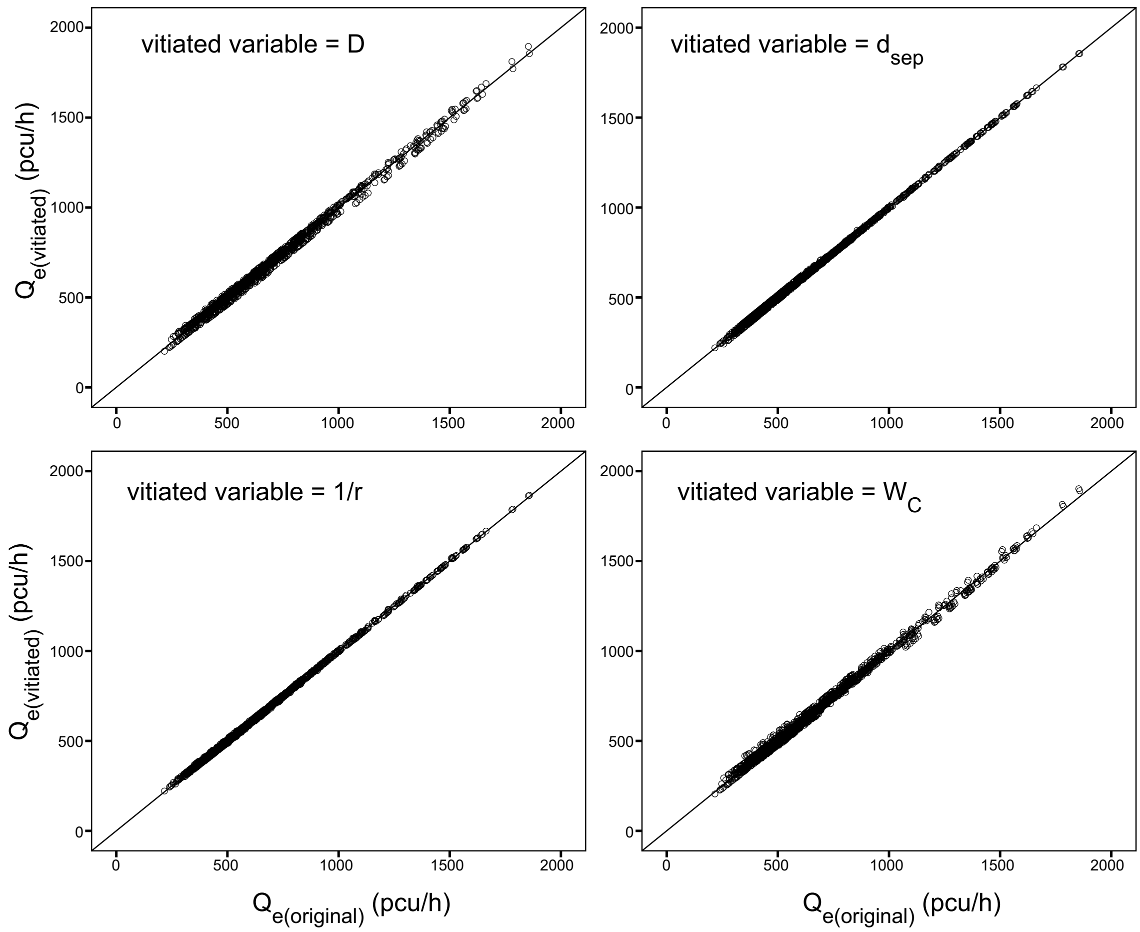


Figure 4-13 Comparison of predicted capacities from original exponential model and exponential model recalibrated with vitiated variables.

Table 4-5 Comparison of RMSE of change in predicted capacities due to use of vitiated variables.

RMSE of change in predicted capacity from original model (pcu/h)	Vitiated variable				
	D	d_{sep}	1/r	W_C	D, d_{sep}, 1/r, W_C
Linear model (recalibrated)	21.4	20.7	8.3	-	-
Exponential model (recalibrated)	17.8	6.4	6.0	18.1	-
Neural network (10-variable, recalibrated)	30.9	25.1	31.4	32.7	34.5
Neural network (10-variable, original)	56.8	12.8	17.2	100.4	148.0

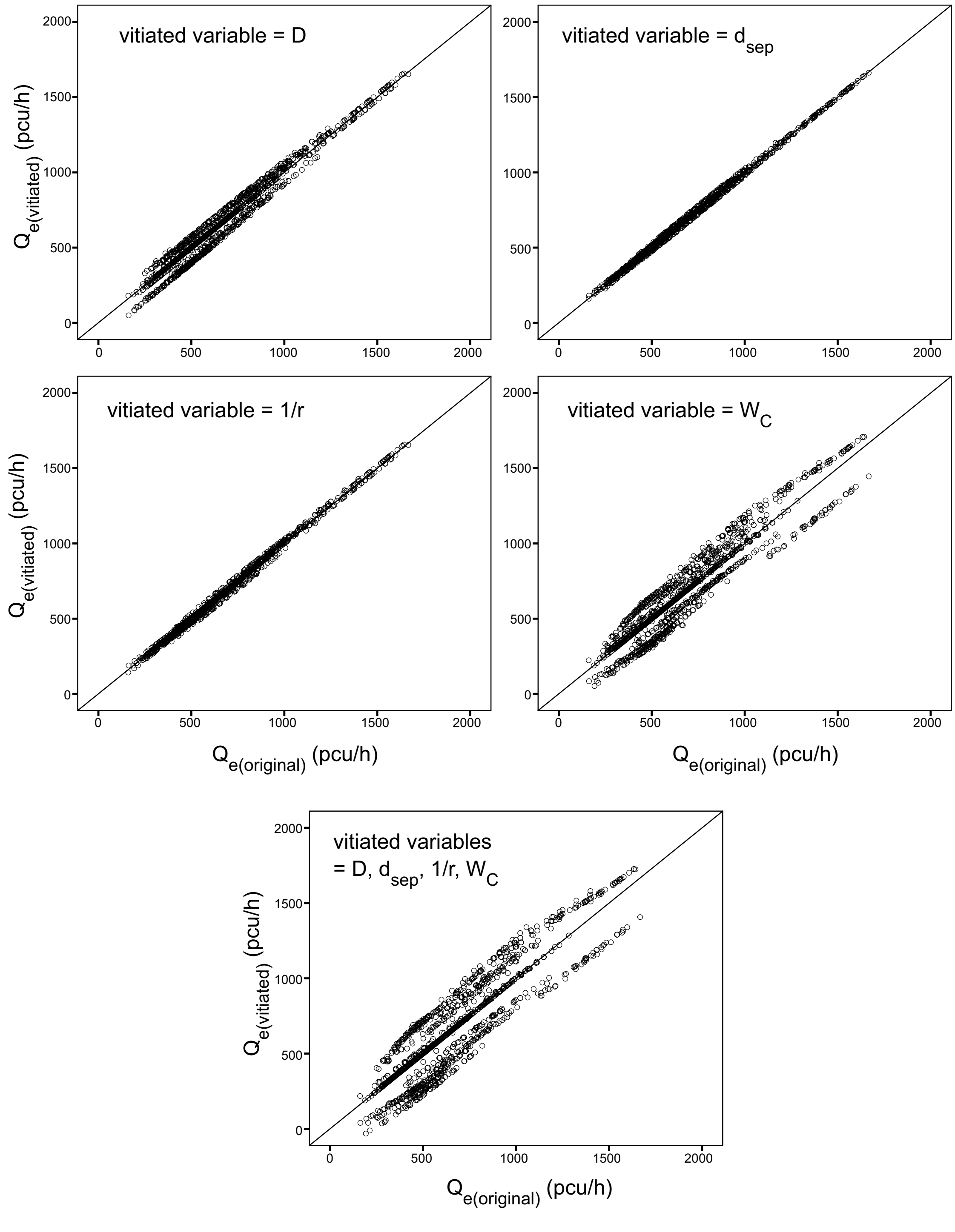


Figure 4-14 Comparison of predicted capacities from original ten-variable NN with accurate and vitiated variables.

The above sensitivity analyses were relatively simple, being based on a particular combination of modified inputs, and ignoring co-variation between the inputs (with the exception of the NN). Nevertheless, they suggest that the regression models appeared not to be overly sensitive to measurement errors in the significant variables, with reasonably small RMSE errors. This was not true for the neural networks, however, which adds further argument against their use as predictive models compared to the regression models.

4.3 Chapter conclusions

An exploratory empirical study on lane entry capacity has been performed using at-capacity flow and geometric data from 35 roundabout entry lanes in Hampshire and Berkshire. There is limited evidence of non-linear relationships between lane entry capacity and circulating flows for individual sites, due primarily to the limited range of observable circulating flows. However, the aggregated data on a wider scale shows a distinct non-linear relationship between entry flow and circulating flow.

Existing capacity models showed relatively limited predictive accuracy for this dataset, with many under-predicting lane entry flows particularly at lower circulating flows. Hence, a linear-in-Q_c model and a nonlinear exponential-in-Q_c model were developed through least-squares regression, where the former accounted for over 82% of the variability in the data and the latter showed similar performance. The linear model provided better fit for several sites, but the nonlinear model had better accuracy at the high and low ends of the circulating flow range. The performances of both regression models were close to the more flexible neural network models which were developed as benchmarks for predictive performance. Model validation tests using a reduced dataset showed that the neural network had poorer transferability, but the empirical models above compared favourably to the best-performing existing models of LR942 and Girabase. The regression models were also found to be reasonably robust against potential measurement errors in the inputs.

It was found that the inclusion of only a few explanatory variables was sufficient to explain most of the variability. Among these, the entry-exit separation distance and exiting flows were found to produce significant contributions to the model fits, more than variables such as entry width and entry angle. However, their interactions with other variables imply a more complex relationship than those which have been found by previous studies. To further investigate these, additional studies were performed into the effects of separation and exiting flow, and these will be discussed in the following chapter.

Chapter 5: Modelling the effects of entry-exit separation and exiting flows on entry capacity

The exploratory empirical study in the previous chapter has provided evidence that the two variables of entry-exit separation distance and exiting flows have significant effects which were more important (in the sense that they could be more useful for capacity prediction in conjunction with other variables) than the more commonly-used variables of entry radius and entry angle. In addition, it has been shown that increasing separation distance or reducing exiting flow could produce non-negative effects on entry capacity, contradicting existing theories. There was thus a clear gap in existing knowledge with regards to the effects of separation and exiting flow, which the rest of the research in this thesis aimed to address.

This chapter thus discusses in more detail the existing literature on the effects of separation and exiting flow, expanding on the reasons for the inconsistencies of these two particular inputs in existing international capacity models as discussed previously in section 2.3. It then describes the rationale for the methodological approach used for further investigation, and explains the model development process used to develop the results. The bulk of this chapter has been presented as a conference paper: YAP, Y. H. (2015) The Impact of Exiting Flows on Roundabout Lane Entry Capacity, 47th Annual Conference of the Universities' Transport Study Group, London, 5-7th January 2015; it has also been submitted for consideration by the Transportation Planning and Technology journal as YAP, Y. H., GIBSON, H.M. & WATERSON, B.J. (under review) The Impact of Exiting Flows on Roundabout Lane Entry Capacity.

5.1 Existing literature on separation and exiting flow

In the literature, the most-widely acknowledged mechanism through which exiting flows and separation distances could affect entry capacity arises from the inability of entering vehicles to distinguish between non-conflicting exiting vehicles and conflicting circulating vehicles until the former leaves the roundabouts, resulting in potentially acceptable lags or gaps between circulating vehicles being partially or wholly rejected. For example, Rodegerdts *et al.* (2006,

Table J-6) observed that at least 10% of entering vehicles hesitated unnecessarily at 6 out of 15 single-lane roundabouts, with 33-40% at two sites. Similarly, Belz *et al.* (2014) found that 3.4–9.3% of entering vehicles exhibited "priority abstaining" behaviour at 5 single-lane roundabout sites, and suggested that the proportion was positively correlated with the exiting flow. Troutbeck also found significant hesitations at 2 out of 8 sites (Troutbeck, 1990) and 10% of vehicles affected at another site (Troutbeck, 1984), and suggested that exiting flows were important where the circulation speeds were higher than expected or where it was particularly difficult to distinguish between circulating and exiting vehicles (Troutbeck, 1990). The occurrence of this phenomenon at several roundabouts was also observed in this study during the surveys described in 0. Various studies based on analytical or simulation methods have illustrated the negative impact on capacity due to this phenomenon with increasing exiting flows (Belz, 2014; Qu *et al.*, 2014; Hagring, 2001; Tan, 1991).

This phenomenon was assumed to be important during the development of the Bovy-Tan capacity model (Tan, 1992) and several French models (Guichet, 1997; Louah, 1992). The Bovy-Tan model form originated initially from microscopic simulation experiments which were designed to model the effects of separation distance and exiting flows on single-lane, single-arm models (Tan, 1992). The French models were based on empirical regression which – given the difficulties of identifying functional relationships from relatively limited and noisy capacity data (Louah, 1992) – likely started with an assumed model form which explicitly included exiting flows as part of the conflicting flow. Hence, these models had a component of the exiting flow added into the major conflicting flow used to calculate entry capacity, so increasing exiting flows for a given circulating flow resulted in reduced capacity.

In contrast, the LR942, SIDRA and HCM 2010 models directly examined the empirical evidence for the above phenomenon during the preliminary stages of their development, and concluded that exiting flows and separation distance were not significant enough to be included as inputs in the final models, at least for the majority of roundabouts. Examples of such early empirical studies in the U.K. included track experiments (Kimber and Semmens, 1977) and surveys on public roundabouts (Semmens *et al.*, 1980; Ashworth and Laurence, 1978; Philbrick, 1977), but these were characterised by relatively small samples in which statistically significant effects of exiting flows could have been difficult to detect.

Furthermore, their data were mainly from roundabouts with very wide circulatory sections (>10 m width), in which exiting vehicles would likely have been easily identifiable early on based on their positions. Track-based studies did not find headway distributions to be influenced by exiting flows (Kimber and Semmens, 1977), while artificially-induced extreme platooning at high circulating flow generated only 10% increases in capacity, so it was concluded that any changes in circulating headways due to exiting vehicles were unlikely to significantly affect capacity (ibid.).

Studies on Australian roundabouts by Troutbeck have been mentioned earlier in this section, but it should also be noted that incorporating the inhibitory effects of exiting flows into gap acceptance models with idealised distributions for headways and critical gaps would not have been a trivial task (Suh *et al.*, 2015; Zheng *et al.*, 2012; Wei *et al.*, 2012; Fortuijn, 2009b; Transportation Research Board, 2007; Mereszczak *et al.*, 2006; Hagring, 2001). The HCM 2010 model assumed that the effects of exiting vehicles were implicitly included within the gap parameters (Transportation Research Board, 2007, p.58) but did not quantify their direct impact.

In contrast to the relationships between separation, exiting flows and capacity ascribed to the inhibitory phenomenon, the empirical Girabase model (Guichet, 1997) suggested that capacity increased with larger exiting flows (apart from large roundabouts with small separation), while the RR142 model for very large roundabouts (Semmens, 1988) found that larger separation reduced entry capacity. The reasons for these unexpected relationships were not given, and when combined with the wider literature discussed above, suggest that there remains a need to develop our understanding of how exiting flows impact on entry capacity.

5.2 Methodology

The three major methods for modelling capacity discussed in Chapter 1 could potentially be applied to the analysis of the effects of separation distance and exiting flows on capacity. Approaches based on gap acceptance theory rely on critical gaps, follow-on headways and circulatory headway distributions, but – notwithstanding several attempts to reconcile some of these with the effects of exiting vehicles (Suh *et al.*, 2015; Qu *et al.*, 2014; Zheng *et al.*, 2012; Mereszczak *et al.*, 2006; e.g. Hagring, 2001) – there are considerable difficulties with regards to determining the values of the relevant key parameters from observable data.

For empirical regression to be used to investigate the effects of separation distance and exiting flow using field data, there must be enough sites to obtain a large enough range of separation distances and exiting flows to identify their functional relationships with capacity. In addition, because the sites also had to have sufficient demand (and hence queueing) for capacity flows to be measured, the survey would have required much wider geographic coverage. The dataset sizes needed to account for the relative noisy nature of measured capacity flows and the multitude of influential variables (for which underlying theoretical relationships with capacity were lacking) would also have required much greater resources than were available for this study. Alternatively, track-based experiments with a representative set of drivers and vehicles would have enabled exiting flows and separation to be investigated while other variables were controlled. However, such experiments potentially involve high costs, major logistical difficulties, health and safety risks, and could also have poor generalizability given the relatively artificial environment.

The relatively complex interactions between individual vehicles in three streams (entering, circulating and exiting) and their stochastic nature suggest that a simulation approach was particularly suited to this study. Simulation also has the further advantage of enabling experiments where many variables could be explicitly controlled. Microscopic simulation based on the kinematic movements and interactions of vehicles was particularly suitable given that the varying speeds and positions of the vehicles were likely to be important determinants of the gap acceptance process in reality. Hence, the microscopic simulation approach was used in this study.

The large number of parameters involved in microscopic simulation modelling, of which many were likely to affect capacity, meant that there was a need for calibration and validation before the models could be used for parametric experimental studies. The case study in section 2.2.5.2 showed that using default parameters without calibration may not accurately reproduce the capacities observed in the field, resulting in doubts over the validity of any findings. Hence, it was necessary to base any models on actual roundabouts where real capacity data could be used for calibration and validation. Furthermore, given the possible sensitivity of capacity to variables such as origin-destination flows or lane use distributions (as suggested by models such as SIDRA or Girabase), the range of experimental variables were limited so that no large deviations from the ground-truth conditions were involved.

5.3 Microscopic simulation software selection

Modern microscopic simulation programs are able to take advantage of much improved processing power and greater developmental resources to allow more comprehensive modelling of roundabouts, compared to early bespoke roundabout simulation programs which were often developed for individual doctoral research projects (e.g. Krogscheepers and Roebuck, 1999; Chung *et al.*, 1992; Tan, 1991; Chin, 1985). Excluding the open-source SUMO (Krajzewicz *et al.*, 2012) whose give-way model remains in development (Krajzewicz and Erdmann, 2013), three different microscopic simulation programs were available for this study: Aimsun (TSS-Transport Simulation Systems, 2011), S-Paramics (Paramics Microsimulation, 2011b) and Vissim (PTV Group, 2013b). An extensive literature-based and hands-on review was thus conducted to select the most suitable one for the purposes of this investigation; the hands-on evaluations were necessary given the proprietary (and hence 'black-box') nature of the programs in which much of the detail of their constituent vehicle behaviour algorithms has not been published. A key criterion was that the software had to be able to model vehicle interactions at a roundabout reasonably accurately without the need to develop bespoke behavioural algorithms, a task which would have been beyond the scope of this study given the necessary data requirements.

The three programs differed in their constituent car-following models (Casas *et al.*, 2010; Duncan, 1997; Fellendorf and Vortisch, 2010), but of likely greater importance to modelling roundabout capacity were their different approaches to junction give-way logic. These were generally based on time-to-arrival of both the minor and major priority vehicles to conflict points based on the intersection of vehicle trajectories (ibid.), although Vissim priority rules used time of arrival and/or clear distance headway to manually-positioned conflict markers (PTV Group, 2013a). Vissim also had a more sophisticated alternative method based on conflict areas, which included anticipative behaviour where drivers could plan ahead in terms of their acceleration profiles (PTV Group, 2013a).

One particular consideration in the context of this study was in the handling of perceived conflict between the nearside entry lane and the inner circulating lane for multilane roundabouts, described earlier in section 2.2.5.2. This conflict could be considered a pseudo–conflict, given that the corresponding vehicle trajectories do not intersect unless the circulating vehicles were leaving at the next exit; despite this, the vast majority (but not all) of nearside entry lane drivers at most roundabouts were observed to give way to vehicles in the inner circulating lane. However, the default network set-up and give-way methods in Paramics and Aimsun essentially resulted in a Boolean response i.e. vehicles from the nearside entry lane either gave-way to all vehicles in the inner circulating lane, or completely ignored them. These two extremes did not reflect behaviour observed in the real world, as, for example, the latter produced much greater capacity flows in the nearside entry lane compared to the offside entry lane. In contrast, Vissim priority rules enabled a more realistic and controllable graduated response for that particular 'conflict' (Cicu *et al.*, 2011).

The geometric accuracy of the microscopic simulation network was a particularly important aspect which affects the give-way behaviour at a roundabout, given the relatively low distances and speeds involved which could magnify errors in network layout and vehicle positioning. Hands-on comparisons of the model network development using example actual roundabouts showed that the link and connector system used by Vissim provided it with much greater flexibility in terms of precise positioning of vehicle trajectories and stopping positions. Aimsun and S-Paramics used link and nodes instead; while they included specific tools to quickly create simple roundabouts with multiple links and nodes, customising them to real roundabout layouts required considerably more effort to match vehicle trajectories with what was observed, given the large number of links and nodes involved.

In addition, the three programs differed in how vehicle free-flow speeds were limited by geometry (as opposed to being constrained by preceding vehicles or own acceleration/deceleration). In Vissim, the speed distributions and the reduced speed areas had to be specified manually using speed data collected from the field, whereas the other models constrained the speeds based on the type of link (in S-Paramics) or curvature (in Aimsun). However, Aimsun required very precise positioning of link internal segments to avoid unwarranted speed changes inside the roundabout, but this was difficult given the relatively complex vehicle trajectories vis-à-vis links outside junctions. Reduced speed areas in Vissim also enabled much greater control over geometry-constrained speed profiles within the roundabout compared to S-Paramics. Notwithstanding the need to collect additional speed data, Vissim thus had a useful advantage in accurate modelling of circulating vehicles speeds in the roundabouts, which was likely to be important for producing the correct gap acceptance behaviour.

Given the possible sensitivity of gap acceptance to the distribution of vehicles on the circulating lanes (for example, an 1800 veh/h circulating flow would effectively leave almost no large gaps if it was constrained to a single lane, but not if spread across two lanes), it was important that the circulating lane usage accurately reflected reality where possible. Lane-usage was affected not just by the origin-destination patterns on the roundabout, but also free lane selection where more than one lane was available for a given movement. However, hands-on testing of the programs revealed relatively frequent unrealistic overtaking/undertaking lane-changes within the roundabout circulation, despite the imposition of lane-change restrictions. These anomalies were eliminated through the use of parallel single-lane links in Vissim to represent individual lanes. Vissim also enabled greater control over the routing of vehicles based on their turning movements, thus producing circulating lane usage patterns which were more consistent with those observed.

The above comparisons (summarised in Table 5-1) showed that Vissim was the best choice for modelling roundabouts for this study, so it was chosen for the rest of the microscopic simulation work below. An additional benefit was that Vissim's ubiquity in published roundabout simulation studies in the past decade meant that it had a useful advantage in terms of peer-reviewed information sources for model development.

Table 5-1 Comparison of microsimulation models (in default form) with regards to key simulation modelling requirements

Simulation requirements	Vissim 6	Aimsun 7	S-Paramics 2011
Geometric accuracy of roundabout network and vehicle trajectories	Relatively simple link and connector structure, easy to fit complex roundabout geometry graphically	Multiple short links (called sections and turnings) required, more difficult to fit geometry accurately	Multiple links and nodes required, more difficult to fit actual geometry accurately
Realistic free-flow speeds of vehicles in roundabouts	Specified manually based on estimates or field data; but reduced speed areas or desired speed decision points allow good control over where local speed changes occur	Speeds based on link curvature and link type, but very sensitive to changes in path curvature, magnified by the geometric difficulties above	Speed distribution based on specified link type and path curvature; less control over local free-flow speeds
Realistic and controllable modelling of free lane selection and vehicle routing	Parallel single-lane links instead of multilane links could be used to prevent unrealistic lane changes in circulation. Vehicle routing through specific lanes also possible.	Less consistent as unrealistic lane changes sometimes observed in multilane circulation (e.g. under/overtaking in circulation).	Less consistent as unwarranted lane changes sometimes observed in multilane circulation, despite some control over lane selection in circulation.
Realistic modelling of pseudo-conflict between nearside entry lane and inner circulating lane	Very good control possible, through lane-specific priority rules	Difficult, due to sensitivity of gap acceptance to conflicting vehicle paths and almost Boolean response	Difficult, due to sensitivity of gap acceptance to conflicting vehicle paths and almost Boolean response
Gap acceptance behaviour which can be easily calibrated	Direct calibration of give-way interactions possible through priority rule or conflict area parameters. Only priority rule modelling was transparent and easily interpreted among all the models here.	Indirect calibration through driving behaviour parameters e.g. acceleration rate.	Indirect calibration e.g. vehicle swept path adjustment. Boolean parameters also provide less control.

5.4 Model development

For the modelling, three roundabout entries were chosen to reflect a range of sizes. This was necessary to investigate the effect of different separation distances, which were likely to vary with the size of the roundabout.

Table 5-2 Roundabout entries modelled in Vissim

Name and Direction	Inscribed circle diameter (m)
hilllane W	31
coralreef NW	62
thornycroft N	92

The links and connectors of the networks were designed on scaled aerial photographs in Vissim to approximately reflect the observed trajectories of vehicles going through the roundabouts (Figure 5-1). Left-turning streams at some entries were however omitted as they either bypassed the circulatory carriageway or there was insufficient capacity data available to calibrate their give-way behaviour. This omission was not an issue as left-turning vehicles had no explicit conflict with vehicles entering at the subject entry, at least for the three roundabouts selected for this study. Where the perceived conflict was likely to be important (particularly in small roundabouts where the left-turning streams were not segregated from conflicting streams), it could potentially be modelled through the addition of appropriate links and connectors for the left entry lane, leading to the circulation links.

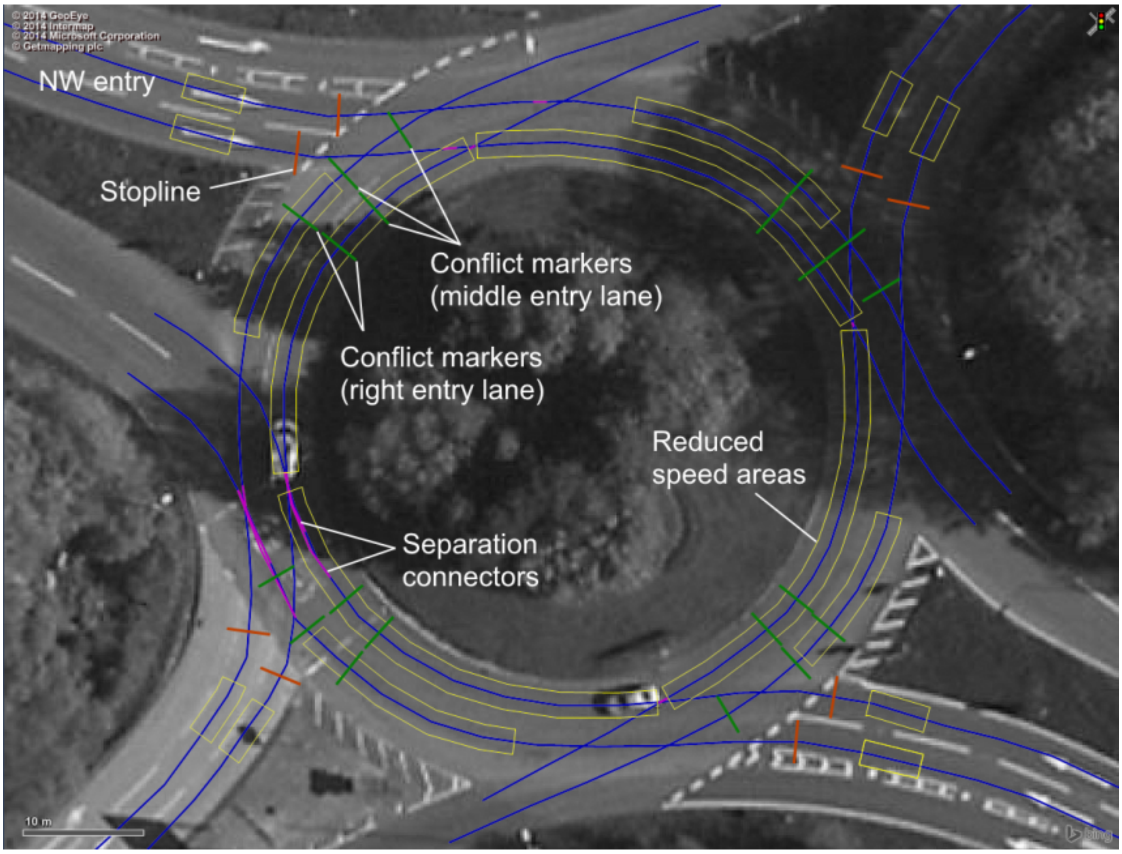


Figure 5-1 Vissim network for Coral Reef NW entry. Screenshot from Vissim (PTV Group, 2013b) which sources default background aerial imagery from Bing Maps: GeoEye, Intermap, Microsoft Corporation and Getmapping plc (2014).

5.4.1 Field data for calibration

Ground-truth lane capacity data for the calibration and validation of the three roundabout models had been extracted from the field data collection described in section 3.5.3. In addition, the mean flows from other entries, turning movements and heavy vehicle percentages were determined for the Vissim model inputs (albeit applied with stochastic variability rather than with exactly-matched actual flow profiles).

The turning patterns for traffic from the south and east entries of Thornycroft N could not be determined as the video was partially obscured, so circulating and exiting vehicles upstream of the west entry were generated from vehicle inputs located on the southwest side of the circulatory carriageway upstream of the west entry. The vehicles were generated in each lane according to an exponential distribution and assigned with a circulation speed distribution as measured.

Table 5-3 Mean entry flows and heavy vehicle percentages from each arm based on sampled video periods

Coral Reef NW	Entry flow (vehicles/hour)				Heavy vehicle percentage (%)			
	NE	SE	SW	NW	NE	SE	SW	NW
Straight	201	1819 X	369 C	3963	1.4	3.8 X	2.7 C	2.8
Right	46 X	72 C	368 C	67	6.3 X	3.1 C	1.0 C	0.0

Hill Lane W	Entry flow (vehicles/hour)				Heavy vehicle percentage (%)			
	N	E	S	W	N	E	S	W
Straight	358	378 X	425 C	376#	1.1	3.2 X	1.9 C	3.2#
Right	14 X	441 C	429 C	342	14.3 X	2.3 C	0.9 C	1.2

#includes left-turning vehicles for W entry; C=circulation and X= exit

Thornycroft N	Flow (vehicles/hour)				Heavy vehicle percentage (%)			
	W	N	other (inner circ. lane)	other (outer circ. lane)	W	N	other (inner circ. lane)	other (outer circ. lane)
Circulating	493	909	292	0	2.0	1.7	1.8	2.6
Exiting	-	-	506	508				

The speed distributions of generated vehicles at the inputs were based on the link speed limits observed on site. However, it was necessary to have more accurate estimates of the distribution of the circulation speeds within the roundabout, as these were likely to influence the accuracy of the gap acceptance behaviour. Hence, the free-flow speeds of at least 100 circulating vehicles passing the splitter island nearest the camera were measured for each roundabout. Where possible, the measurements were segregated by circulating lane and origin of circulating vehicle, although there was very limited data for circulating vehicles originating prior to the SW entry of Coral Reef (Figure 5-2). In Coral Reef, it was found that vehicles in the inner circulating lane travelled at lower speeds compared to those in the outer circulating lane due to their smaller-radii trajectory; the opposite occurred at Thornycroft, possibly because the larger radii enabled more aggressive drivers (with higher preferred speeds) to choose the offside lane to achieve higher speeds. It was also observed that vehicles originating from the first entry upstream did not necessarily have lower speeds (due to their need to accelerate) compared to those circulating around the island from previous entries. The resulting speed distributions were then applied to the reduced speed areas of the roundabout models (Figure 5-1). The extent and location of the reduced speed areas were based on the estimated positions where vehicles were observed to accelerate and decelerate, and were consistent with typical measured roundabout speed profiles (Li *et al.*, 2013; Vaiana and Gallelli, 2011; Cicu *et al.*, 2011).

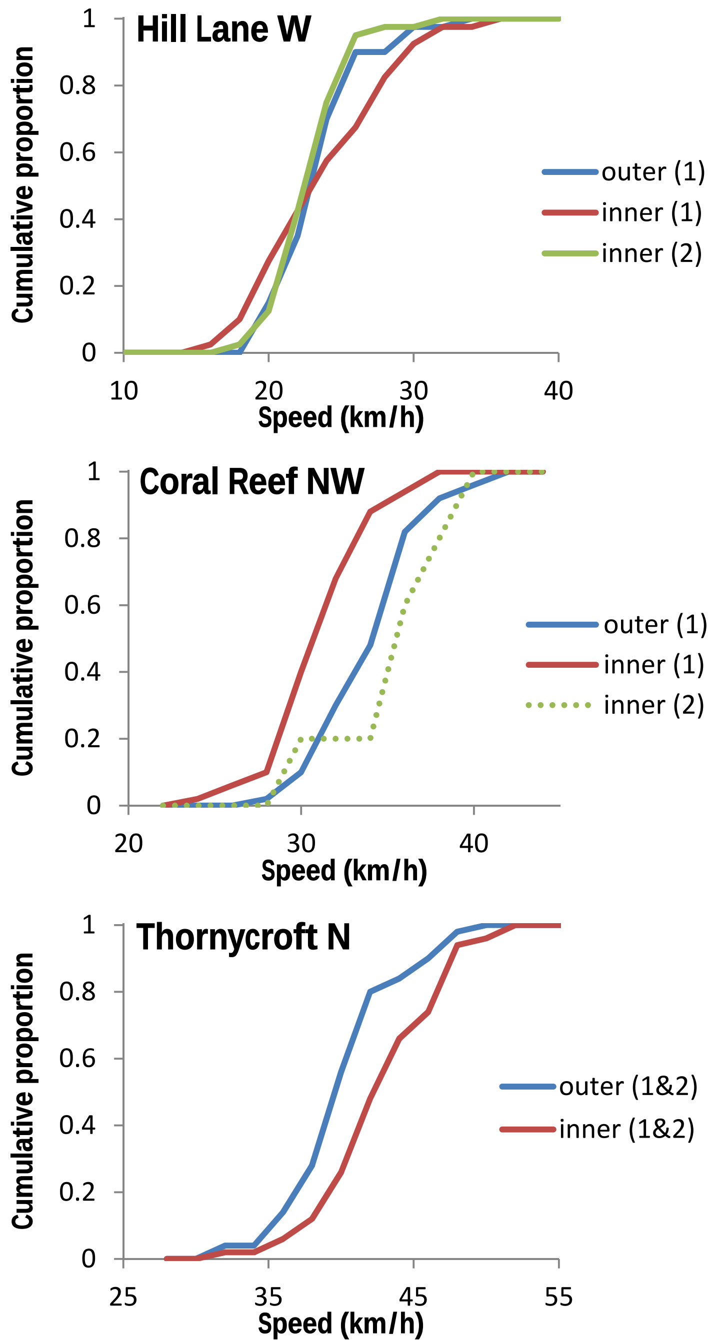


Figure 5-2 Measured speed distribution from the three roundabouts disaggregated by circulating lane; (1) denotes vehicles originating from first entry immediate upstream, (2) from other entries further upstream.

5.4.2 Give-way behaviour

To model the give-way behaviour at the entry, priority rules were used. They operate by withholding entry priority at the stopline if there are any conflicting vehicles present within specified minimum time gaps and distance headways measured from the corresponding conflict markers in a given time-step. The priority rules were initially configured based on the default suggested by Vissim's developers (PTV Group, 2013a) and from previous studies such as Li *et al.* (2013). However, with the suggested time gap settings, it was found that positioning the conflict markers between 2.6 to 9.3 metres upstream of the default (determined iteratively for each roundabout entry) enabled entering vehicles to more realistically merge closer behind the circulating vehicles and avoid impeding the following circulating vehicles. Frame-by-frame video analysis also showed that the majority of entering vehicles began crossing the give-way line just before the circulating vehicles had fully cleared the downstream corner of the splitter islands, which could only be replicated by releasing vehicles earlier through positioning conflict markers more upstream.

Another modification adopted from Li *et al.* (2013) was to increase the time gap for the nearside entry lane - inner circulating lane conflict marker to 2.5 seconds, as this provided a better match to the observed lane capacity curves, and prevented vehicles entering from the nearside lane from colliding with those leaving the inner circulating lane towards the next exit. Also, the offside entry lane conflict markers at both circulating lanes were specified with equal time gaps of 2.6 seconds (with an additional 1 second for heavy vehicles). The Vissim user manual (PTV Group, 2013a) and Hagring (2000b) both suggested that the gap for the inner circulating lane should be slightly larger than that for the outer lane, but estimated critical gaps in the inner lane could have been more affected by exiting vehicles, while equal time gaps here gave the closest match with the actual capacity curves for each lane. These priority rule parameters were applied to both Coral Reef NW and Thornycroft N entries, and are illustrated in Figure 5-3 and Table 5-4.

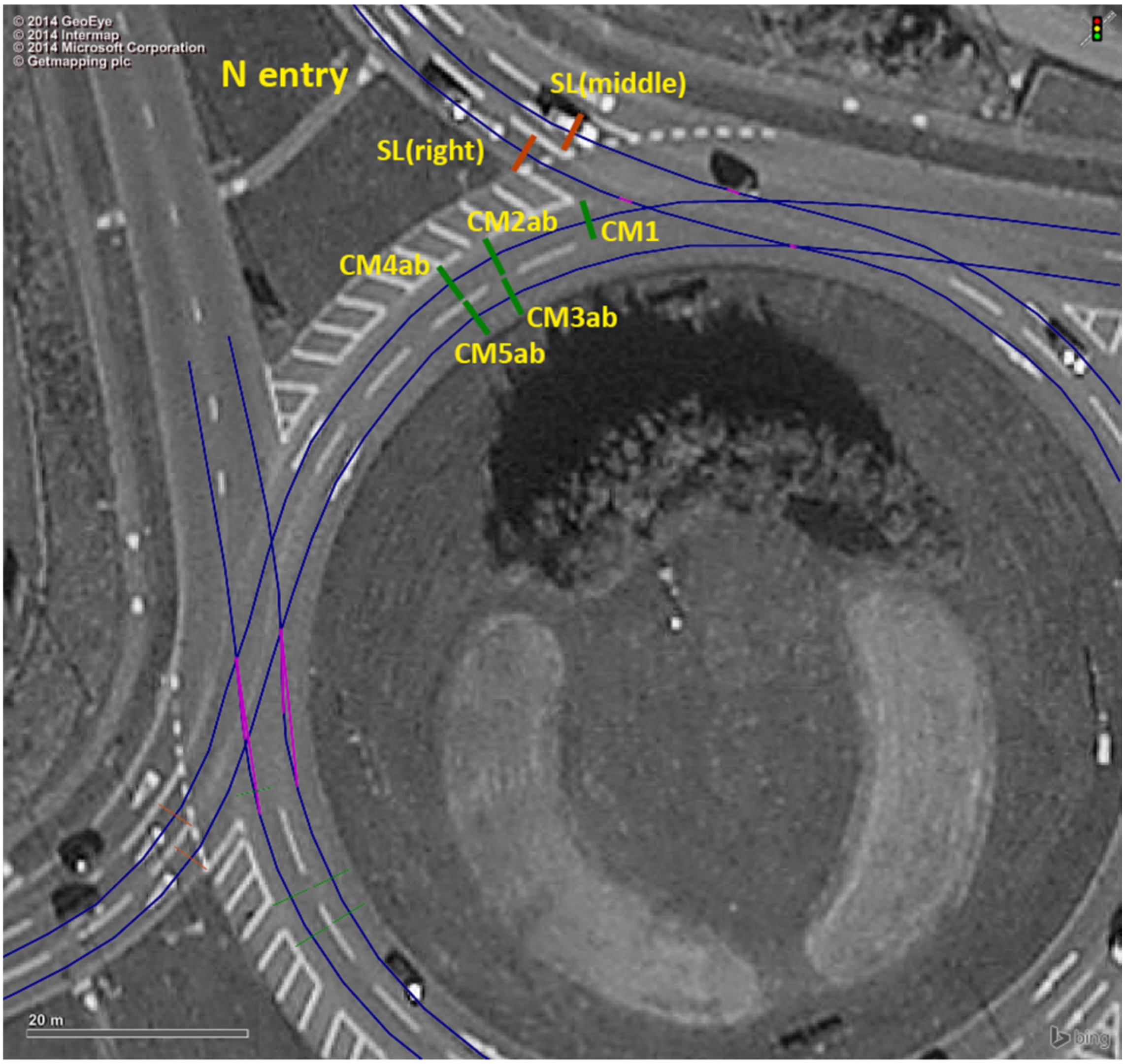


Figure 5-3 Priority rule configuration for Thornycroft N – screenshot from Vissim (PTV Group, 2013b) which sources default background aerial imagery from Bing Maps: GeoEye, Intermap, Microsoft Corporation and Getmapping plc (2014).

Table 5-4 Conflict marker settings for Thornycroft N, corresponding to Figure 5-3.

Conflict marker	Stop-line SL	Vehicle types (entry)	Vehicle types (circulating)	Max. speed (km/h)[#]	Min. gap time (s)	Min. "headway" (m)[@]
CM1	Left	All	Heavy	180	0.0[$]	5.0[$]
CM2a	Left	All	All	180	2.6	0.0
CM2b	Left	Heavy	All	180	3.6	0.0
CM3a	Left	All	All	180	2.5	0.0
CM3b	Left	Heavy	All	180	3.5	0.0
CM4a	Right	All	All	180	2.6	0.0
CM4b	Right	Heavy	All	180	3.6	0.0
CM5a	Right	All	All	180	2.6	0.0
CM5b	Right	Heavy	All	180	3.6	0.0

[#] The conflict criteria do not apply to conflicting vehicles exceeding this speed; a high value of 180 km/h essentially means that they apply to all vehicles.

[@] The term "headway" as used in Vissim actually refers to the critical distance (measured upstream from the conflict marker) in which any conflicting vehicle present would cause the stop-line to block entering vehicles. A value of 0 means that this distance-based criterion is ignored.

[$] This default rule prevents vehicles from the nearside entry lane from colliding into the side of long HGV's in the outer circulating lane; the minimum time gap becomes redundant and is thus set to zero.

For the small Hill Lane W roundabout, the lower speeds and distances involved meant that vehicle lengths needed to be allowed for to avoid merge conflicts. The conflict markers described previously were specified with nominal distance headways and reduced time gaps so as to release vehicles only after the rear of the circulating vehicles had passed, shown in Figure 5-4 and Table 5-5. Additional low-speed conflict markers (CM1 and CM8 in Figure 5-4) were used to prevent unrealistic merge conflicts causing stoppages in the circulation flow. For example, CM8 (with experimentally-determined parameters) was used to detect slow but high-accelerating vehicles crossing the give-way line from the immediate upstream entry; otherwise the priority rules overestimated their time of arrival by not taking into account their accelerations.

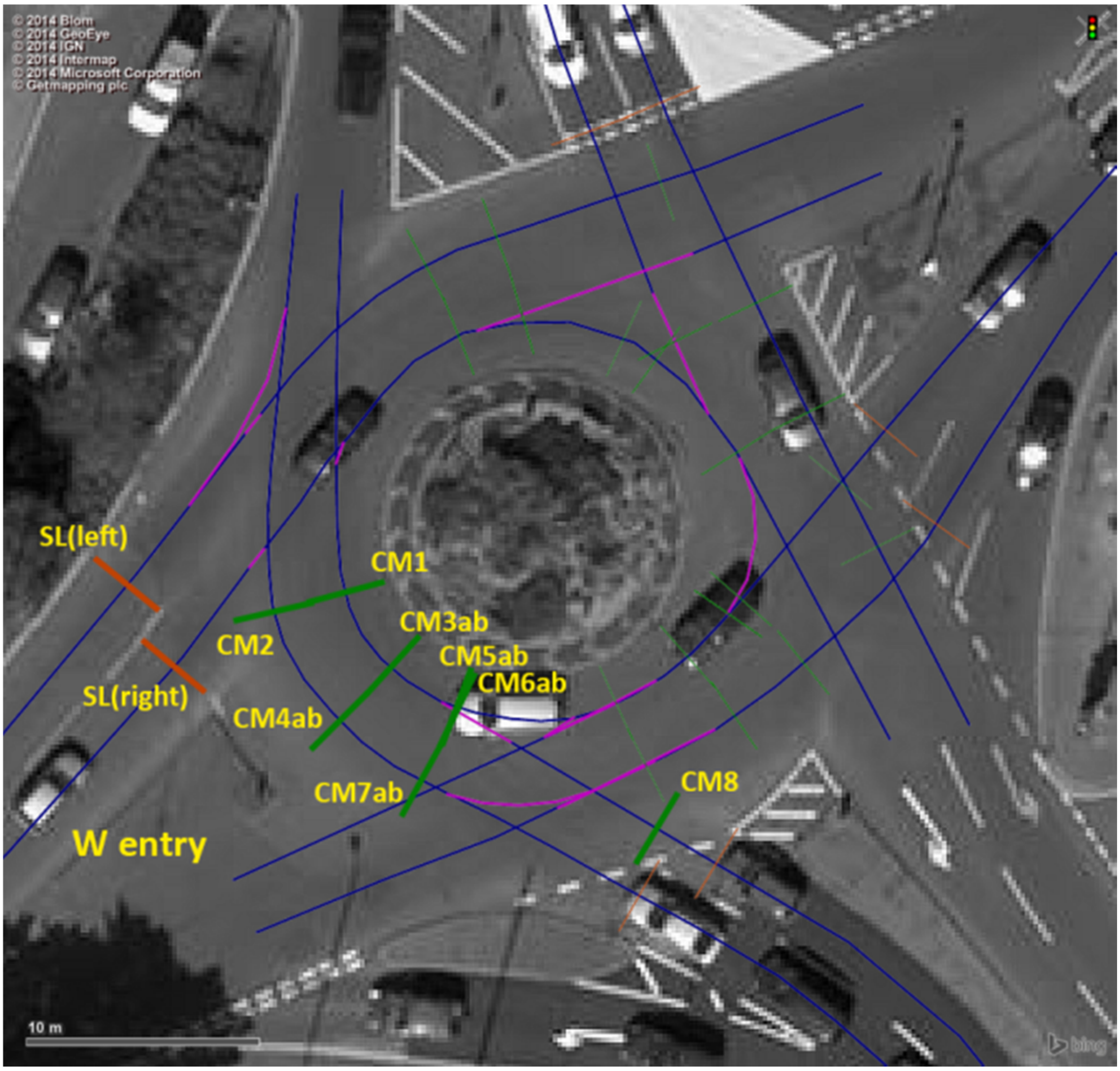


Figure 5-4 Priority rule configuration for Hill Lane W – screenshot from Vissim (PTV Group, 2013b) which sources default background aerial imagery from Bing Maps: Blom, GeoEye, IGN, Intermap, Microsoft Corporation and Getmapping plc (2014).

Table 5-5 Conflict marker settings for Hill Lane W, corresponding to Figure 5-4; explanatory footnotes for Table 5-4 also applicable here.

Conflict marker	Stop-line SL	Vehicle types (entry)	Vehicle types (circulating)	Max. speed (km/h)	Min. gap time (s)	Min. "headway" (m)
CM1	Right	All	All	15	0.0	5.0
CM2	Left	All	Heavy	180	0.0	5.0
CM3a	Left	All	All	180	2.3	0.1
CM3b	Left	Heavy	All	180	3.3	0.1
CM4a	Left	All	All	180	2.4	0.1
CM4b	Left	Heavy	All	180	3.4	0.1
CM5/6a	Right	All	All	180	2.4	0.1
CM5/6b	Right	Heavy	All	180	3.4	0.1
CM7a	Right	All	All	180	2.4	0.1
CM7b	Right	Heavy	All	180	3.4	0.1
CM8	Right	All	All	13	1.6	3.0

5.4.2.1 Conflict area modelling alternative

Vissim's conflict area modelling was also explored as the developer-recommended alternative to priority rules. With conflict area modelling, approaching vehicles have more anticipatory behaviour which is more reflective of real-world driving, in which they either adjust their acceleration or deceleration profile based on their observation of conflicting vehicles, including those downstream of the conflict area. Vehicles in the major stream also behave similarly, thus slowing down if necessary to avoid colliding with entering vehicles (PTV Group, 2013a).

However, even with adjusted parameters, vehicles were entering only after circulating vehicles left the conflict area at the next exit (Figure 5-5). This unrealistically hesitant entry behaviour resulted in much lower capacities than observed, and reflected issues also experienced by other researchers, such as Li *et al.* (2013) who found that the maximum rejected gaps and accepted gap were larger and less consistent for conflict areas compared to priority rules. Along with other difficulties such as setting the correct stopping positions (these depended on the length of the conflict areas and in turn the overlapping section of the links), this meant that priority rules were the preferred method of modelling the give-way mechanism, despite its limitations.

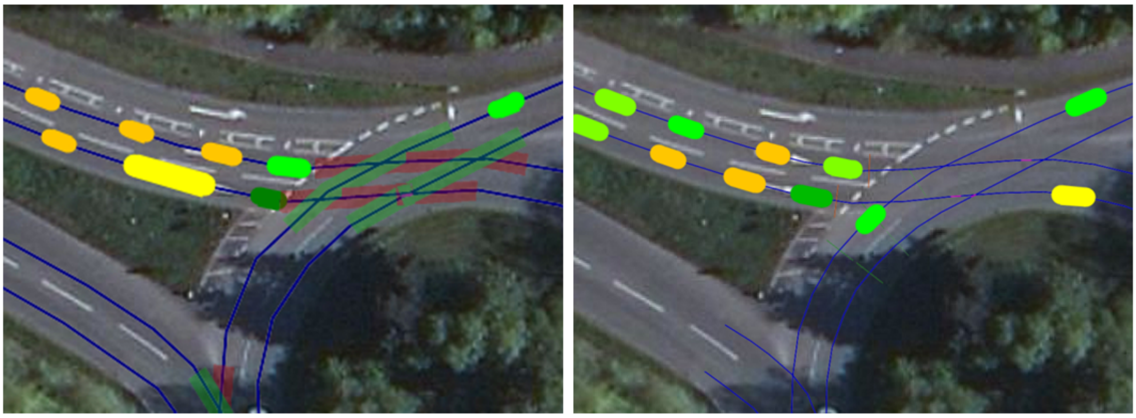


Figure 5-5 Comparison of the last circulating vehicle's position in the time step when the first vehicle on the middle lane begins accelerating, with conflict areas (left) and priority rules (right) – adapted screenshots from Vissim (PTV Group, 2013b) which sources default background aerial imagery from Bing Maps: GeoEye, Intermap, Microsoft Corporation and Getmapping plc (2014).

5.4.3 Simulated vehicle behaviours

It was not possible to measure from field data many of the other characteristics of vehicle behaviour in this study (e.g. acceleration profiles, vehicle lengths, standstill distances, etc.) so model parameters were generally left as the defaults based on prior research (Fellendorf and Vortisch, 2010). Side-by-side comparisons of the movements of vehicles in 3D animations from simulation and in the videos showed that the modelled driving behaviours matched reality reasonably well (Figure 5-6).

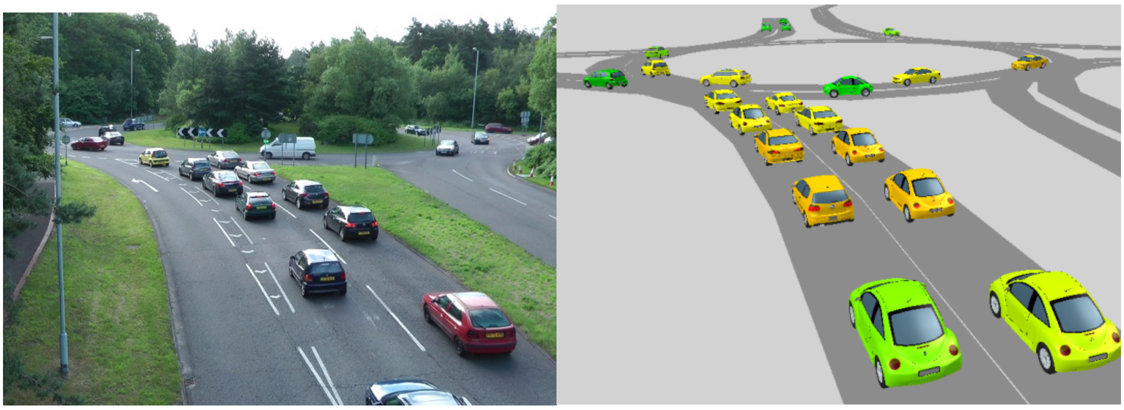


Figure 5-6 Screenshots from video and Vissim animation for Coral Reef NW.

5.5 Model calibration

The initial calibration of the simulation models was based on comparing the exponential regression curves of entry flow against circulating flow derived from one-minute flows during periods of continuous queueing. It was found that the parameters above produced good matches with the actual capacity curves for Coral Reef NW and Hill Lane W, but underestimated capacities for Thornycroft N (Figure 5-7). There was thus a need for further calibration.

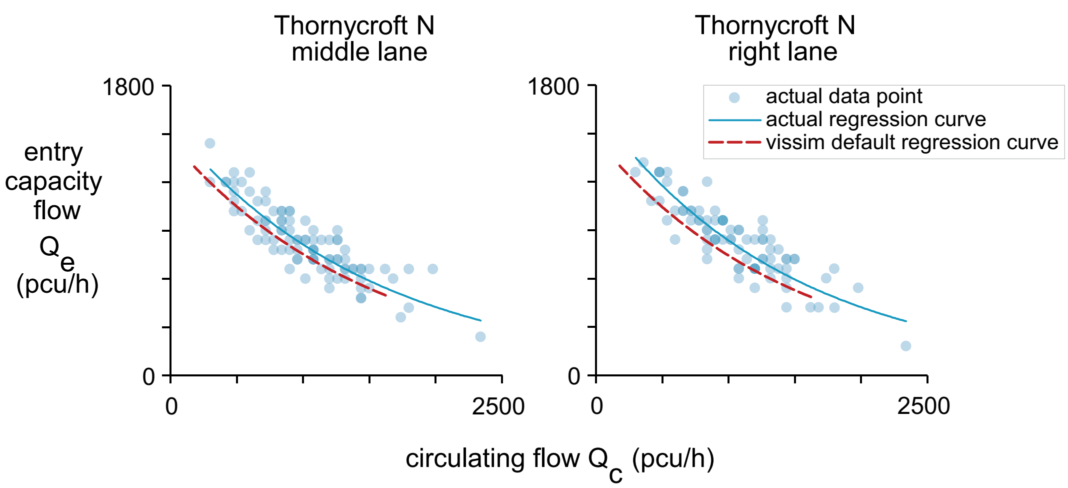


Figure 5-7 Actual Thornycroft N capacity regression curves compared against the regressed capacity curves from Vissim with default settings.

A review of the literature showed little consensus among researchers, industrial practitioners and public organisations on calibration methods for Vissim roundabout models. Calibration approaches used by researchers were generally on a case-by-case basis, where the measures used for calibration through comparisons with empirical data have included critical gaps and/or follow-on headways (Li *et al.*, 2013; Cicu *et al.*, 2011; Peterson *et al.*, 2008), speeds (Vaiana *et al.*, 2012; Vaiana and Gallelli, 2011; Keen *et al.*, 2008), travel times (Valdez *et al.*, 2011), headway distributions (Fortuijn, 2009b) and capacity (Hummer *et al.*, 2014; Wei *et al.*, 2012).

In addition, several car-following and gap acceptance parameters in Vissim have been found to affect the entry capacity of roundabouts (Li *et al.*, 2013; Wei *et al.*, 2012; Cicu *et al.*, 2011). Computational approaches to calibrate multiple parameters (e.g. genetic algorithms or neural networks) have previously been used (Vasconcelos *et al.*, 2014a; Vasconcelos *et al.*, 2014b; Ištoka Otković *et al.*, 2013; Duong *et al.*, 2011; Park and Qi, 2005), but there was a real risk in this case of over-fitting the models given the relatively limited field data (less than 100 capacity data points for each roundabout entry lane) and the large number of model parameters. Another problem was that it was not possible to determine whether the optimised parameter values were suitable without detailed data such as vehicle kinematics. It was thus decided to select specific parameters for calibration based on measures which could be determined using available resources from field data.

Towards this, one possible approach considered was to calibrate priority rule time gaps using critical gaps estimated from field data (Li *et al.*, 2013; Cicu *et al.*, 2011). However, field observations in this and other studies (Wei and Grenard, 2012; Xu and Tian, 2008) suggested that exiting flows likely impact on rejected headways and therefore critical headway estimates. In particular, critical gaps become significantly overestimated due to the inhibition caused by exiting vehicles (Suh *et al.*, 2015; Zheng *et al.*, 2012; Wei *et al.*, 2012; Fortuijn, 2009b; Transportation Research Board, 2007; Mereszczak *et al.*, 2006; Hagring, 2001); there is yet to be an estimation method which adequately allows for this without incommensurate approximations such as assuming every exiting vehicle would have circulated at an average speed (Zheng *et al.*, 2012; Mereszczak *et al.*, 2006). In addition, the maximum likelihood method of Troutbeck (1992) – widely agreed to be the best method of estimating mean critical gaps from the field (Brilon *et* *al.*, 1999) – typically assumes a log-normal gap distribution, which contrasts with the constant time gaps of Vissim. The critical gap and Vissim time gap are thus not directly comparable, so it was decided to leave the time gaps unchanged across the models.

Li *et al.* (2013) and Wei *et al.* (2012) calibrated Vissim's default car-following model (Wiedemann, 1974 as cited in Fellendorf and Vortisch, 2010) parameters using mean follow-on headways between successive vehicles entering the same gap. To a certain extent, as suggested by Suh *et al.* (2015), Wei and Grenard (2012) and Xu and Tian (2008), follow-on headways could also be partly affected by exiting vehicles, since drivers can make their gap acceptance decisions during their approach. However, they had the key advantage over critical gaps of being directly measurable and directly comparable between the model and the field.

By comparing follow-on headway distributions from each model with at least 138 actual follow-on headway measurements for each site, the Wiedemann 1974 additive and multiplicative car-following parameters were changed from the defaults of 2 and 1 respectively to 0.5 and 4 for Thornycroft N, 0.1 and 6 for Coral Reef NW and 0.1 and 4 for Hill Lane W. These modified parameters were applied over 40m-long sections at the entries and yielded follow-on headways which approximately matched those from the field (Figure 5-8), as shown by independent samples t-tests on the mean values (Table 5-6). The only exception was for Coral Reef NW – given that the Wiedemann 1974 additive parameter could not be further reduced while increasing the multiplicative parameter increased the mean, it was not possible to more closely match the mean follow-on headways. Despite this, the Coral Reef NW capacity curves showed a good match (Figure 5-9), while the follow-on headways showed a much improved fit compared to the pre-calibrated default values.

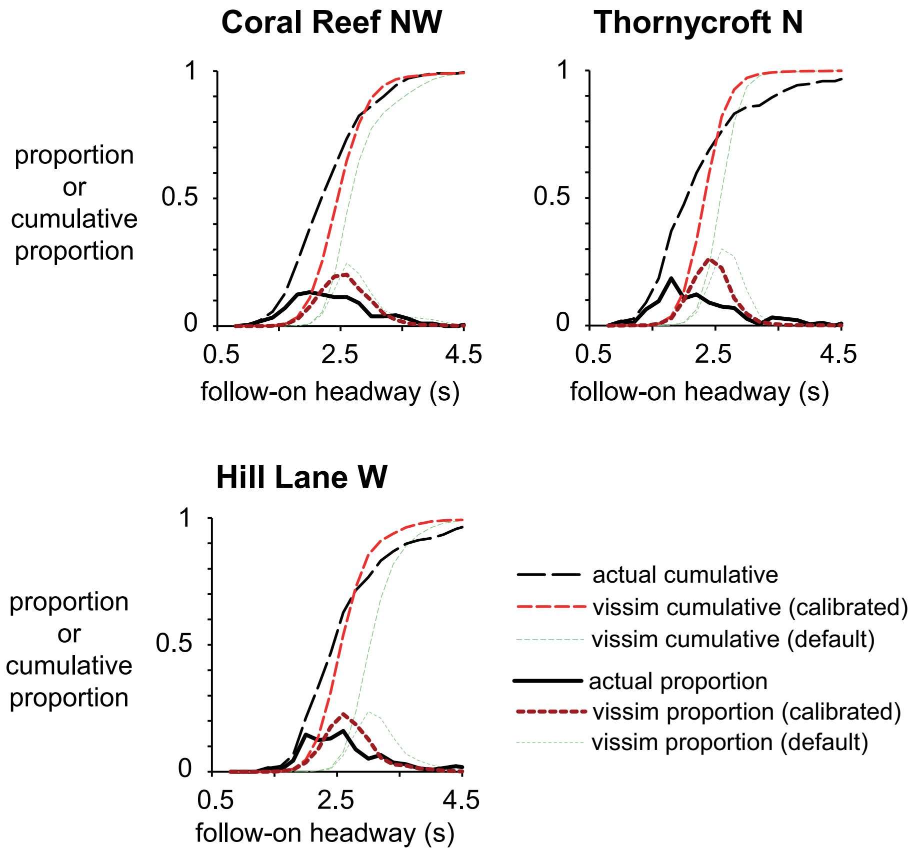


Figure 5-8 Comparison of actual and Vissim follow-on headways before and after calibration

Table 5-6 Comparison of actual mean follow-on headways against those from the Vissim models, before and after calibration.

Site	Source	Mean (s)	Standard deviation (s)	t-test P value (2-tailed, compared against actual mean)*
ThornycroftN	Actual	2.25	0.90	-
	Default Vissim	2.60	0.29	<0.001
	Calibrated Vissim	2.35	0.34	0.158
Coral Reef NW	Actual	2.28	0.64	-
	Default Vissim	2.61	0.43	<0.001
	Calibrated Vissim	2.51	0.52	<0.001
Hill Lane W	Actual	2.67	0.95	-
	Default Vissim	3.10	0.43	<0.001
	Calibrated Vissim	2.63	0.46	0.639

*Levene's test showed that the variances of the actual and Vissim follow-on headways were not equal at the 10% significance level for all cases.

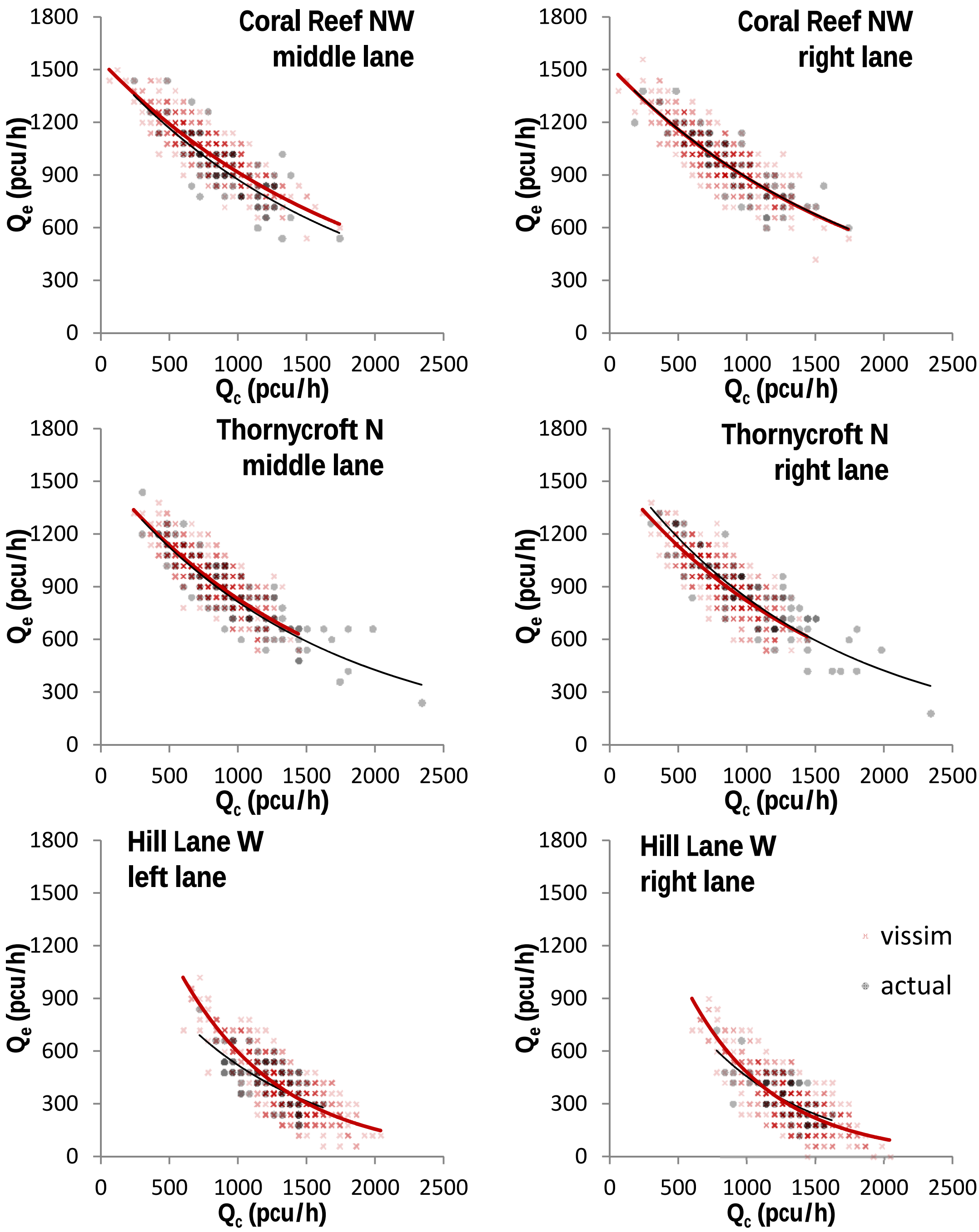


Figure 5-9 Capacity curves from actual and Vissim calibrated models for the three sites, with all exiting flows routed through middle separation point.

It should be noted that this method of calibration using follow-on headways should be regarded as an approximation since follow-on headways in reality are likely to depend on the drivers' anticipation of available gaps when they arrive at the give-way line, rather than maintaining safe distances to the preceding vehicle *per se* as assumed in car-following algorithms. Nevertheless, using this calibration method, the RMSE's for ThornycroftN middle lane and right lane capacities reduced from 147.9 and 122.4 pcu/h to 112.1 and 102.8 pcu/h respectively, while also providing good fits for the capacity curves of the other two sites (Figure 5-9).

5.6 Stochastic modelling of separation distances

Microscopic simulation in Vissim inherently introduces stochasticity into various elements of the model such as vehicle generation, speeds and accelerations. In contrast, the link and connector network is fixed, resulting in all modelled vehicles merging, diverging or travelling along exactly identical trajectories. Examination of driving behaviours in the field in this and other studies (St-Aubin *et al.*, 2013a; Mussone *et al.*, 2011; Salter and Al-Alawi, 1982) however showed that vehicles – even with identical turning movements – often had slight differences in their trajectories through roundabouts, depending on their sizes, initial positions, speeds and accelerations. Because of these, it is possible that different vehicles could be recognised as leaving the circulation at different positions relative to the entry, resulting in varying entry capacities as earlier exiting drivers would have less of an inhibitory effect. This issue was thus investigated through a small study from a driver perspective.

5.6.1 Driver perception of exiting separation distances

The separation point is essentially the point on the circulation at which drivers at the entry can begin to distinguish exiting vehicles from circulating vehicles. A small trial study was conducted to investigate how the position of the separation point may vary from an individual driver's perspective. This involved a subject (with over 15 years driving experience including roundabouts) watching edited video clips recorded from the kerbside of the Old Wokingham Road / Nine Mile Ride roundabout north entry, from the perspective of a driver waiting at the give-way line and seeking a safe gap to enter into (Figure 5-10). During the video playback, the subject was asked to press one of two buttons the instant he could discern whether an oncoming vehicle was circulating or exiting the roundabout. A custom-made VBA application in Microsoft Excel was used to control the video playback and record the relevant timestamp data.

Figure 5-10 Example video screenshot for turning intention experiment, from the Old Wokingham Road / Nine Mile Ride north entry, looking south-west.

To minimise bias, the video clips were equally split between exiting and circulating vehicles, with random playback order used. Where a wrong decision was made, the result was discarded so as to reduce the effects of random guessing (although this was unlikely to be completely eliminated). The trial was repeated 10 times by the same subject over a period of several weeks; the results did not show a learning effect manifested in decreasing response times for each video (Figure 5-11).

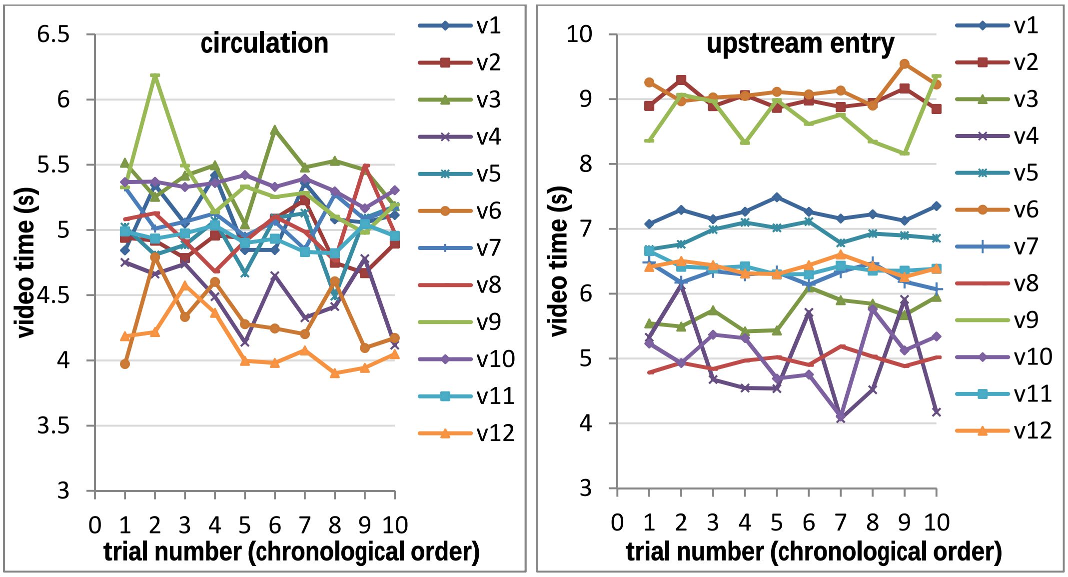


Figure 5-11 Recorded timestamps for 12 vehicles each from circulation and upstream entry; the video times were from the start of each video clip.

The position of the separation points and corresponding separation distances for each of the 12 vehicles from the circulation (from the south or east entries) and 12 vehicles from the first upstream entry (the west entry) were estimated from a combination of the recorded timestamps, scaled aerial photographs and known crossing times over reference points based on visible features of the roundabout. The separation points for the sampled vehicles were found to vary over a fairly long section (Figure 5-12). Most of the variation was due to the differences in separation point between different vehicles rather than repeated measurements from the same vehicle (Figure 5-13).

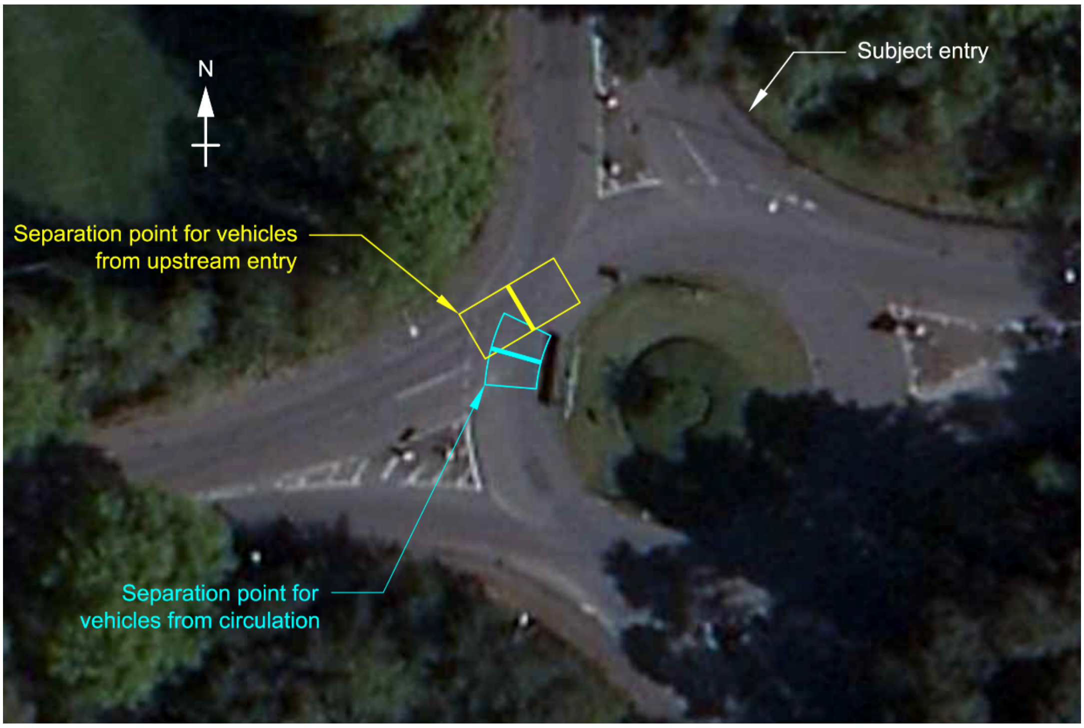


Figure 5-12 Estimated mean position of separation points (±1 standard deviation) for Old Wokingham Road / Nine Mile Ride north entry (background photo from DigitalGlobe (2013)).

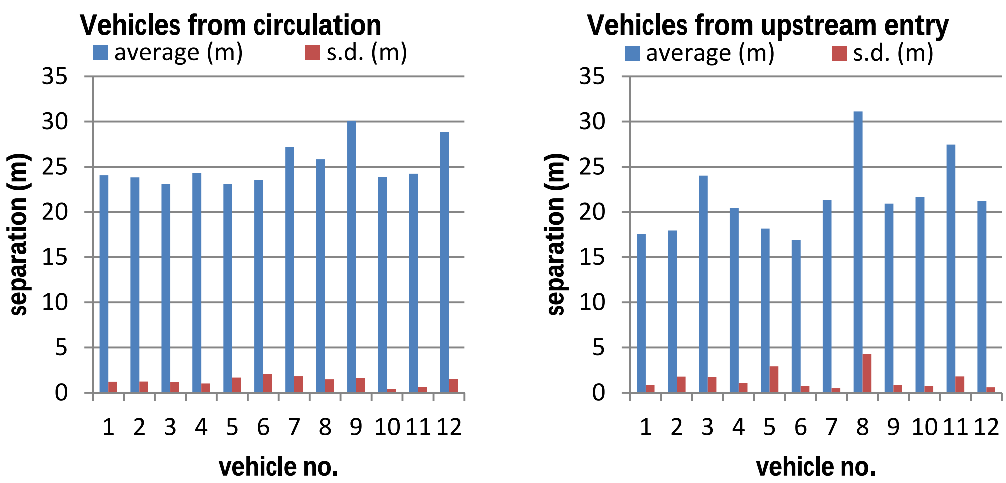


Figure 5-13 Comparison of calculated separation distances where vehicles 1-6 are circulating, 7-12 are exiting (s.d. = standard deviation); larger separation distance indicates earlier identification.

It was observed in this small experiment that differences in separation points for individual vehicles could be attributed to the vehicles' lateral position and attitude, changes in speeds, and/or their use of turn signals. Generally, exiting vehicles from the circulation could be identified earlier due to their positioning on the carriageway or their speeds or acceleration, since exiting vehicles were positioned on the outer circulating lane, had higher speeds and tended to accelerate rather than decelerate as they approached the separation point.

Several circulating vehicles turning from the south to the east used turn signals but these tended to be quite late when they were already near the separation point or were somewhat difficult to see in the video due to the ambient lighting conditions; several other vehicles turning north from the east entry also tended to leave their right-turn signals on until they exited, leading to possible erroneous decision-making. Hence, the decisions were not based entirely on the observed turn signals.

Several vehicles in the west entry began signalling to exit while they were queuing. For those which did not, it was not possible to identify them until there was a perceptible difference in speed or trajectory after they crossed the give-way line. There was increased variation for these particular vehicles, depending on whether the decision on their turning intention was made when the turn signal was first seen or when there were additional indications such as lateral movement. The point at which exiting vehicles can be definitively identified is likely in practice to depend on the subject driver's risk aversion, the approaching vehicle speed or other factors, as well as his/her adherence to the Highway Code (Department for Transport, 2007a, Rule 170).

The reaction time involved in the experiment was minimised by ensuring that the subject only had to press one of two ergonomically-optimised buttons, with his fingers resting lightly on those buttons during the experiments. An alternative approach considered was based on pausing video playback at selected distances and recording the subject's response; however, this could compromise the perceived or estimated speeds and accelerations of the oncoming vehicles, when these were likely important for decision-making in gap-acceptance. Moreover, given that this study was focussed on the variability of the separation point, it could also be argued that the effects of individual reaction time should be included in the measurements as well.

Aside from the issue of reaction time and limited sample size, there were other limitations to this experiment. The limited video image size and resolution could potentially lead to a delay in perceiving, say, changes in tyre direction or turn signals. The field-of-view on the video was much smaller than that for a driver in the real world, and so the subject was unable to distinguish between vehicles originating from the south or east arms, where this could allow the driver to better predict the likely turning movement for some vehicles. Furthermore, the camera height and angle did not accurately reproduce the drivers' view, thus possibly biasing the results (since a higher viewpoint allows a clearer view of the position of the oncoming vehicle relative to the circulatory carriageway). In reality, the driver's viewpoint is often not stationary either, since drivers can often make gap acceptance decisions while approaching or queuing before arriving at the give-way line. Also, the vehicles entering from the entry on the right were generally in a long queue rather than approaching at speed; in the case of the latter, it could be expected that exiting vehicles slow down more than circulating vehicles and thus could be identified further upstream before the give-way line.

For vehicles from the circulation, the separation point based on centreline geometry (Figure 3-1) was around 4.8 m downstream of mean position (or 2.3 m outside of one standard deviation) estimated from this video-based study. However, the video-based separation point represents a best-case scenario in that the subject focussed only on the oncoming vehicle. In reality, the driver is likely to split his attention across several vehicles which are in potential conflict and so could be slower to react or decide. In addition, there is likely to be a difference between the point at which an oncoming vehicle can first be identified as exiting or circulating, and the point at which the driver is certain enough to make a gap-acceptance decision; the latter is likely to be when the oncoming vehicle has moved further along its trajectory (depending on the risk aversion of the entering driver). The effective separation point (based on perception and risk) could thus be nearer the geometric separation point.

This trial experiment suggests that there are two separation points for an entry at a typical roundabout, and there is some variability inherent in their positions, caused by turn signal use, vehicle trajectories and speeds. Some variation is also likely to be intra-driver as well as inter-driver, although verifying the latter will clearly require more subjects for the experiment. To better understand the variables which affect the separation point, more videos from a greater variety of roundabouts would be required, although for practical application, the extended study would necessarily need to relate the definition of the separation points to the geometry and O-D patterns of the roundabout.

5.6.2 Modelling the stochasticity of separation distances in Vissim

The driver perception study above has shown clear evidence of variability in effective separation distances due to differences in the signal use and trajectories of individual vehicles in the circulation. This stochastic phenomenon has not previously been explored or included in previous studies, which due to methodological constraints, typically assumed that exiting vehicles diverged from the circulating vehicle trajectory at a fixed point. For example, in the case of microscopic simulation – which normally aims to reflect the stochastic processes occurring in the real world – link and node or connector networks typically cannot be easily changed during a simulation run without causing problems for the car-following algorithms, and thus it is not possible to model changes in separation distances stochastically.

In the context of this study however, it was particularly important to include this variability in separation distances, as they were likely to have an impact on entry capacities due to the inhibitory effects described in section 5.1. In reality, drivers at the entry in the model typically had no advanced knowledge of the turning intention of the oncoming vehicles in the circulation until they passed the notional separation point; this lack of advanced knowledge is also inherently modelled in Vissim, as the exiting vehicles are on a path conflicting with entering vehicles until they diverge onto the exit link.

A novel method of introducing stochasticity into the separation points in Vissim was developed, whereby exiting vehicles could leave the conflicting path at multiple separation points rather than at a single separation distance. However, it was not possible from the driver perception study above to identify a suitable theoretical distribution of separation distances for the position of these points. Hence, for a simplified replication of the effect of vehicles being randomly identified as leaving the circulating stream at different distances in Vissim, additional short connectors to the exit link upstream of the subject entry were connected to the circulation link at three different points. The earliest separation point was approximately limited by either the estimated sightlines from the entry, or where exiting vehicle paths became tangential to the circulation path (Figure 5-14). The late separation point was based on the estimated trajectory of vehicles leaving at the last possible moment without excessively slowing down, whereas the middle separation point was approximately the trajectory taken by the majority of observed vehicles.

The connectors were made deliberately short, to avoid merge conflicts caused by a faster vehicle following a slower one attempting to overtake before the connectors merged onto the exit link; these would be due to a temporary break in car-following rules as they travelled on different connectors before arriving at the exit link.

The impact of varying separation distances was then investigated by routing different proportions of exiting vehicles through these early, middle and late separation points. The random routing of individual vehicles thus mimicked the random exiting points of vehicles observed in the driver perception study.

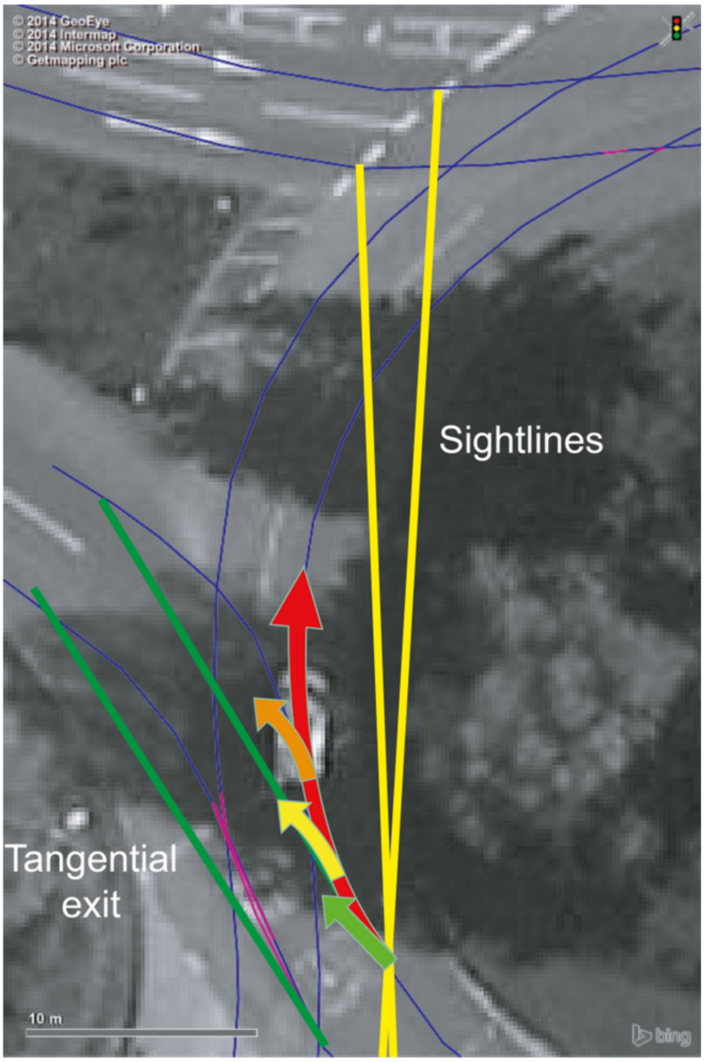


Figure 5-14 Exaggerated illustration of the modelled separation points from the inner circulating lane of Coral Reef NW – adapted screenshot from Vissim (PTV Group, 2013b) which sources default background aerial imagery from Bing Maps: GeoEye, Intermap, Microsoft Corporation and Getmapping plc (2014).

5.7 Chapter conclusions

This chapter has explained the background and methodology for a microscopic simulation investigation into separation and exiting flows. It has been shown that PTV Vissim had particular advantages for the modelling of multi-lane roundabouts, despite several simplifications in its modelling of gap acceptance behaviours. For calibration of modelled capacity, it was shown that the use of follow-on headways was preferable to the use of critical headways, given that they could be directly measured and compared.

A small study based on videos recorded approximately from drivers’ perspective at a different roundabout suggested that the positions where exiting vehicles could first be identified depended on their use of turn signals, their acceleration profiles and their trajectories. For example, exiting vehicles perceptibly accelerated and left the circulation on a tangential path, whereas other vehicles did not accelerate and remained on the circular trajectory. The trajectories and accelerations – and thus effective separation distances – varied between vehicles, but it was not possible to identify a suitable theoretical distribution for the effective separation distance within this study.

Given the random nature of these separation distances, a novel method of introducing stochastic variability into separation distances in Vissim was thus developed, based on the use of multiple connectors at the exit. This was necessary as variation in separation points was likely to impact on capacity, due to inhibitory effects. The resulting models form the bases for the analyses and investigations in the following chapter.

Chapter 6: The effects of entry-exit separation and exiting flows on entry capacity: Results and Discussions

Following on from the previous chapter, this chapter presents the results from the microscopic simulation study into the effects of separation distance and exiting flows. It then discusses the possible mechanisms for these effects, and explains the development of new hypothesised relationships between separation, exiting flow and capacity which were then used to develop a revised empirical model for capacity based on the work in the Chapter 1. The bulk of this chapter has been presented as a conference paper: YAP, Y. H. (2015) The Impact of Exiting Flows on Roundabout Lane Entry Capacity, 47th Annual Conference of the Universities' Transport Study Group, London, 5-7th January 2015; it has also been submitted for consideration by the Transportation Planning and Technology journal as YAP, Y. H., GIBSON, H.M. & WATERSON, B.J. (under review) The Impact of Exiting Flows on Roundabout Lane Entry Capacity.

6.1 Analyses and Results

The models developed as described in the preceding chapter were used for experimental investigations. For each scenario, 40 simulation runs with different random seed numbers were used to account for the stochasticity of the microscopic simulation, with initial warm-up periods to develop queued capacity conditions at the subject entry. For each run, flow data from one simulated hour were measured using data-collectors in one-minute intervals, and heavy vehicles assumed to be equivalent to 2 passenger car units (pcu), consistent with the field data collection.

6.1.1 The impact of separation distances

Figure 6-1 shows that the entry capacities at Thornycroft N were largely insensitive to where exiting vehicles left the circulation. In contrast, the proportion of late-exiting vehicles had a clear negative impact in the other two roundabouts, particularly for the right entry lanes; the proportion of middle-separating vehicles was also influential at Hill Lane W.

Examination of the range of assigned vehicle speeds, time gaps and the effective separation distances in the model showed that these results depended on the proportion of exiting vehicles which encroached into the critical distances relative to the conflict markers defined by vehicle speed × time gap (Figure 6-2 and Figure 6-3). If none of the exiting vehicles encroached into these critical distances (such as for light vehicles from Thornycroft N middle lane, which like the other entries comprised about 97% of all vehicles), the proportions of early-/middle-/late-exiting vehicles had no impact on the entry capacity. At the other extreme, if all vehicles exited inside the critical distances, there were greater reductions in capacity when proportionally more vehicles separated later than earlier (as at Hill Lane W). At Coral Reef NW, the right lane appeared to be particularly sensitive to the late-exiting flow, as the majority of the critical distances ended between the late- and mid-separation points. In contrast, the middle lane was only marginally affected as fewer vehicles with higher speeds had critical distances which exceeded the late-separation distance. The contrast between the two lanes of Coral Reef NW suggests that the effect of exiting vehicles may explain differences in entry capacity between different lanes at some roundabout entries, due to the smaller separation distances for offside entry lanes.

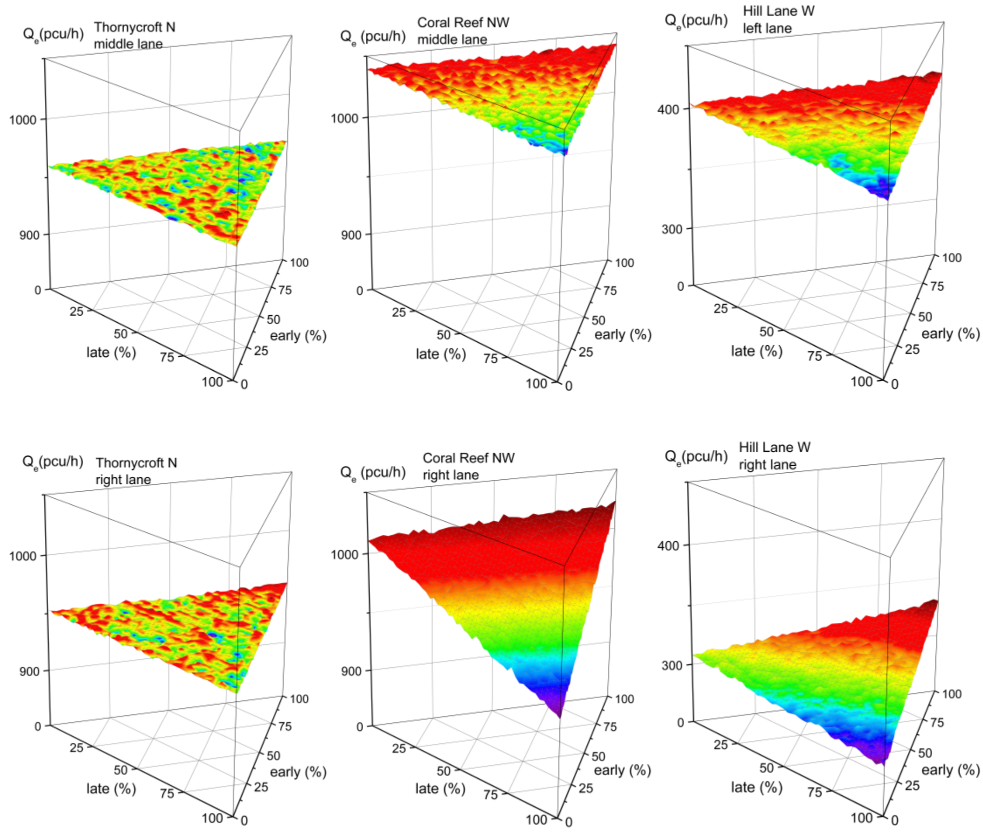


Figure 6-1 Mean entry capacities against proportions of exiting flow routed through early, middle and late separation points; colours and vertical scale emphasise surface gradients.

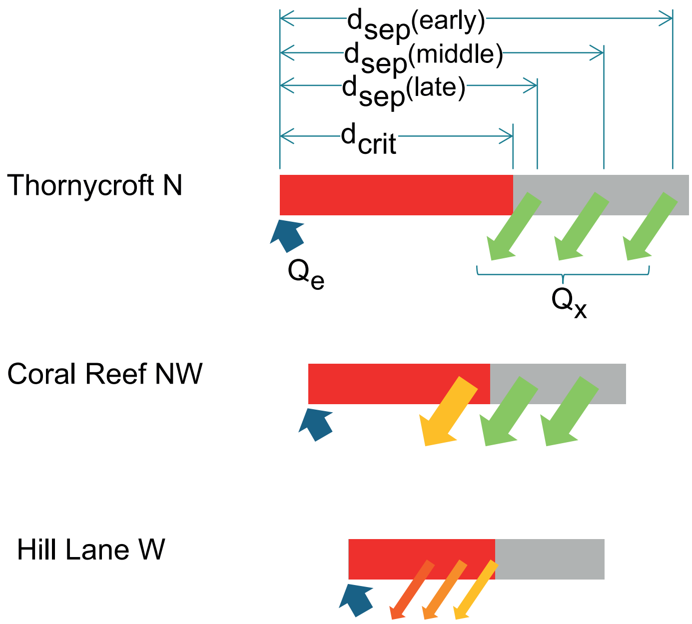


Figure 6-2 Simplified illustration of the positions of separation points (d_{sep}) relative to typical critical distances (d_{crit}) of light vehicles.

Taking into account the differences between early- and late-separation distances and the exiting flows, the reductions in capacity from 100% early-exiting to 100% late-exiting were greater in Hill Lane W compared to Coral Reef NW. If the changes in entry capacity were expressed as pcu/h reduction per m of separation per 1000 pcu/h of exiting flow, the figures for the right and left lanes of Hill Lane W were about 20.2 and 8.7 respectively, compared to 4.6 and 0.6 for Coral Reef NW right and left lanes; the corresponding figures for Thornycroft W were less than 0.16. These values reflected the order in which inhibitory effects were significant at these roundabout lanes, with Hill Lane W being particularly strongly affected as its circulating speeds (and hence critical distances) were relatively high for its small diameter. Figure 6-4 illustrates how there was a greater reduction not just as the roundabout sizes (and hence separation distances) reduced, but also as the separation distance decreased from the nearside to the offside entry lanes.

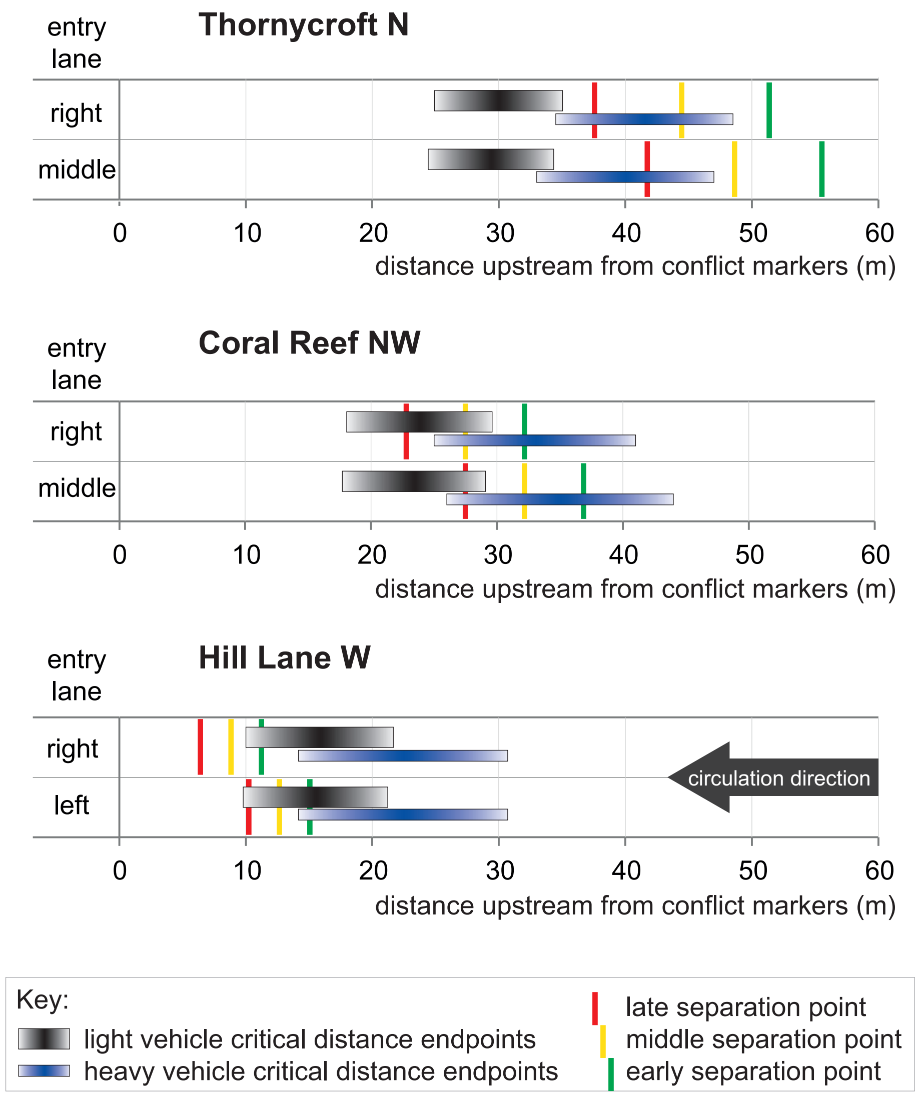


Figure 6-3 Relative positions of separation points and critical distance endpoints (averaged across both circulating lanes) for the six modelled entry lanes.

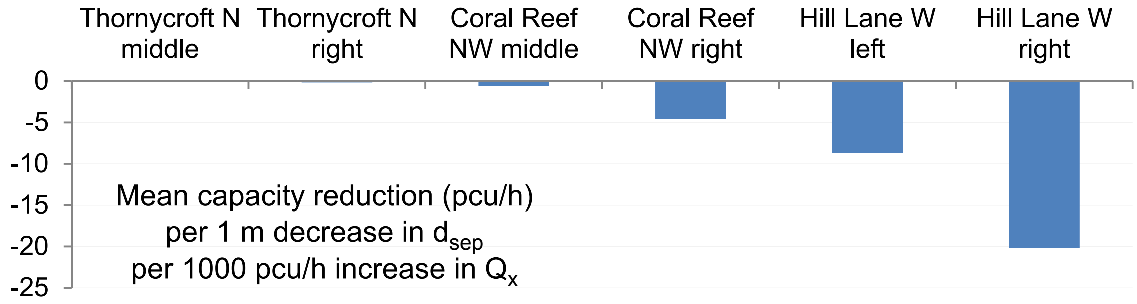


Figure 6-4 Comparison of the capacity reductions of the roundabout entry lanes after allowing for differences in separation flow and separation distances.

6.1.2 The impact of exiting flows

The stochastic variations in the simulation produced a range of exiting flows over which the effects of different exiting flows on entry capacity could be observed. Assuming that all exiting flows left at one separation point, models in the form of $Q_e=Ae^{BQc}+C$ – similar to that previously developed with field data in section 4.2.1 – were regressed from the Vissim dataset for each roundabout and the residuals plotted against exiting flows (Figure 6-5). There was a clear linear relationship between the residuals and exiting flow as shown through local regression (loess) lines, aside from the apparent reduction in the slope of each line for Coral Reef NW right lane (likely arising from circulatory carriageway capacity limitations causing high correlation between circulating and exiting flows e.g. Pearson r = 0.95 when $Q_x + Q_c > 3100$ pcu/h and $Q_x > 2000$ pcu/h in the Vissim model). The linear relationship was generally positive apart from at the right entry lane of Hill Lane W, where there was a clear reduction in gradient as the separation distance decreased and the inhibitory effect increased.

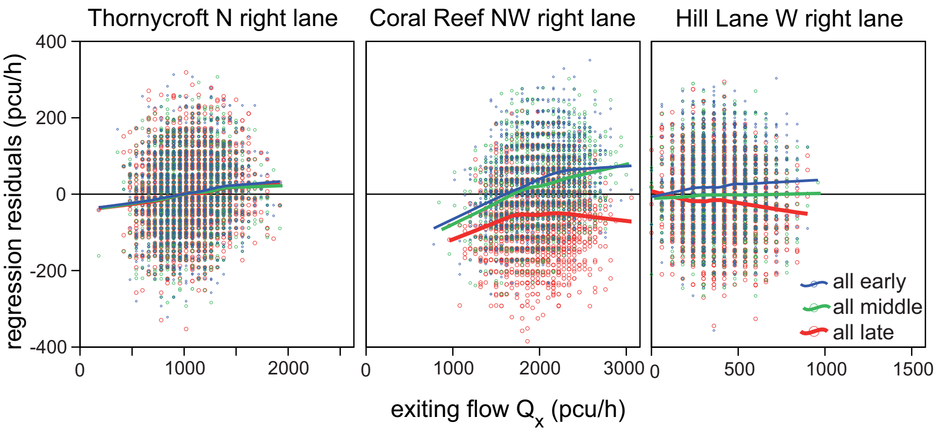


Figure 6-5 Residuals from $Q_e=Ae^{BQc}+C$ regression plotted against exiting flow.

6.2 Explanatory mechanisms for the effects of separation and exiting flow

Several mechanisms have been explored to explain some of the observed impacts of separation distances and exiting flows on capacity.

6.2.1 Inhibitory effect

The increasingly negative effect of exiting flows as separation distance decreases, as shown in section 6.1, is the result of the inhibitory effect where entering vehicles are unable to distinguish exiting vehicles from circulating vehicles until they reach the separation point. As explained previously through Figure 6-2, this is an issue only when the separation points lie within the critical distance, which is a function of the size of the minimum acceptable time gap and the circulating speeds. It results in greater capacity reduction as the exiting flows increase, and the separation distances decrease.

Hence, the extent to which the inhibitory effect occurs depends on how early exiting vehicles can be identified by entering drivers, as this defines the separation distance. If proportionally more exiting vehicles can be identified earlier (i.e. the separation distance was greater), the capacity reduction from the inhibitory effect is smaller.

However, the modelling here was based on early and late separation points which were estimated based on sight distances and likely trajectories for exiting and circulating vehicles; it was assumed that these were likely to provide the earliest and the latest positions by which exiting vehicles could be distinguished from circulating vehicles. In reality, the position of the separation point may not necessarily be based on trajectory and sightlines alone. For example, in Figure 6-6, exiting and circulating vehicles follow the same trajectory up to point S, and if both have the same speed profile prior to arriving at point S, they are then indistinguishable up to point S. However, if the trajectories result in different speed profiles for the exiting and circulating vehicles, the separation point should be based on where the speeds begin to differ (point S’ in Figure 6-6) rather than where the paths diverge (point S).

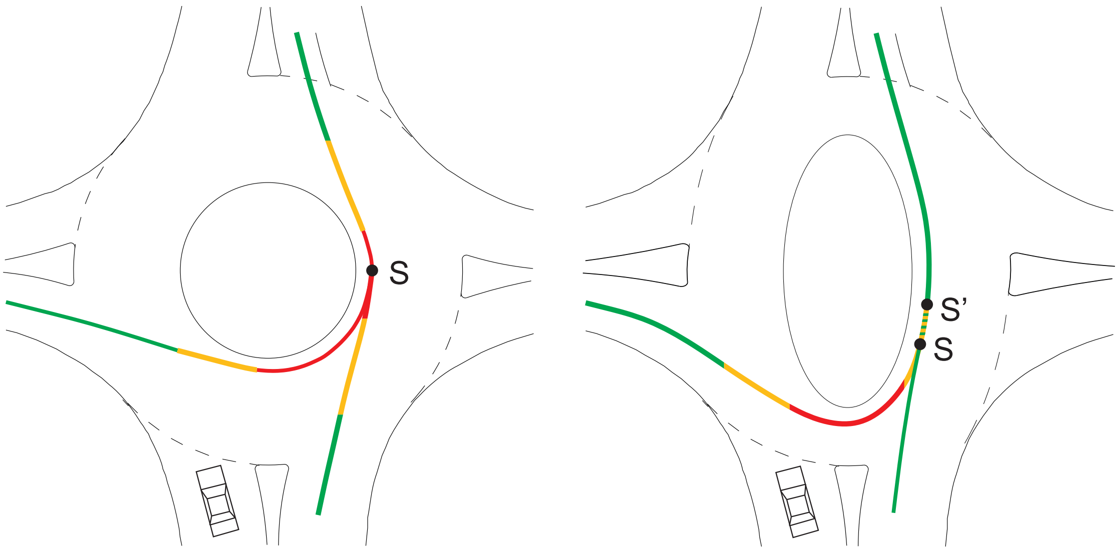


Figure 6-6 Comparison of through and circulating vehicle speeds in circular and non-circular roundabout (green fastest, red slowest); circulating vehicles perceptibly decelerate at S’.

The separation point could also depend on the origin-destination movements and lane choices of the vehicles, as these result in differences in trajectories, speeds and accelerations (Mussone *et al.*, 2011). The exiting and circulating vehicles may use different lanes, so entering drivers could distinguish between them based on their lane positions in the circulating carriageway. Turn signals may also be used by oncoming vehicles to indicate their turning intention to entering drivers. The position of the separation point is also likely to differ from driver to driver at the entry, depending on visual acuity, eye heights and driving experience. For example, an experienced driver who is very familiar with the behaviour of vehicles at the roundabout and their predominant turning patterns may be able to distinguish between exiting and circulating vehicles earlier than an unfamiliar driver. Other factors include sight distance obstructions on the central island, which could limit judgment on the speed and trajectory of oncoming vehicles. Similarly, given that some drivers may start making gap acceptance decisions on the approach before reaching the stopline, their visual perspective on the approach could also influence how quickly exiting vehicles are recognised.

6.2.2 Circulating headways

The results in section 6.1 suggest that exiting flows had an inherently positive impact on entry capacity unless separation was low and inhibitory effects dominated. It was possible that this was due to changes in the gaps of the circulating stream as the number of exiting vehicles increased. To investigate this, further analyses were performed using the Thornycroft N model, which was chosen for its minimal inhibitory effects from exiting vehicles; all heavy vehicles were also excluded from the entry for this reason. The model was simplified to a single circulating lane to magnify any platooning effects caused by exiting vehicles, while flows from the first entry immediately upstream (i.e. the west entry) were also omitted. Further simulation runs were then performed with different combinations of exiting and circulating flows in 25 veh/h intervals, up to an assumed 1700 veh/h circulation capacity. It was found that larger proportions of exiting vehicles left more gaps of around 3.1 seconds and less of around 2.6 seconds in the circulation headways, along with a smaller peak at around 4.5 seconds (Figure 6-7). These were the result of individual or successive exiting vehicles leaving gaps behind in platoons of circulating vehicles, with stronger effects at larger circulating flows where platooning was greater.

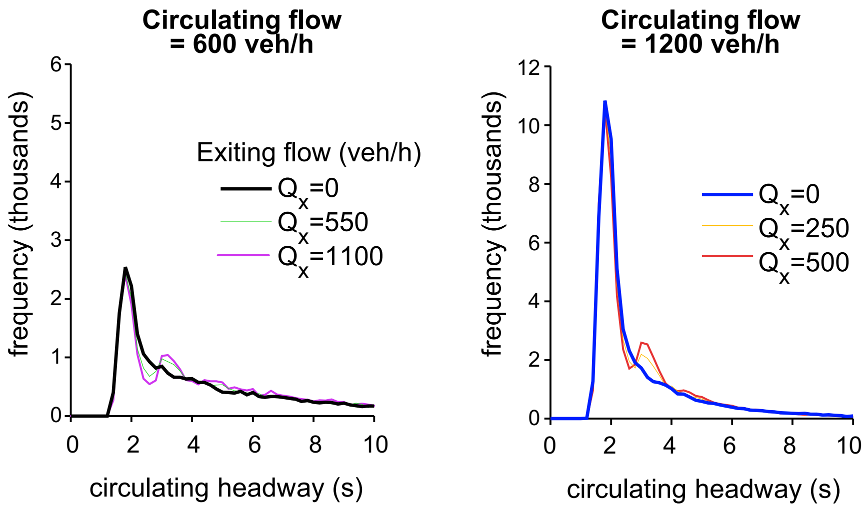


Figure 6-7 Circulating headway distributions from simplified Thornycroft N model (numbers denote mean circulating/exiting flows in veh/h).

To determine the net impact of these altered headway distributions on capacity, the differences between the mean entry capacity at each flow combination and the mean entry capacity at the corresponding Q_c with zero Q_x were plotted (Figure 6-8). Ignoring the apparent trends in the horizontal direction arising from fitting a $Q_e=Ae^{BQc}+C$ model at $Q_x=0$ (necessary to interpolate the corresponding Q_c values at $Q_x=0$), there appears to be a positive relationship where entry capacity at a given circulating flow increases with larger exiting flows. This was particularly evident at the higher range of circulating flows, where headways were generally smaller.

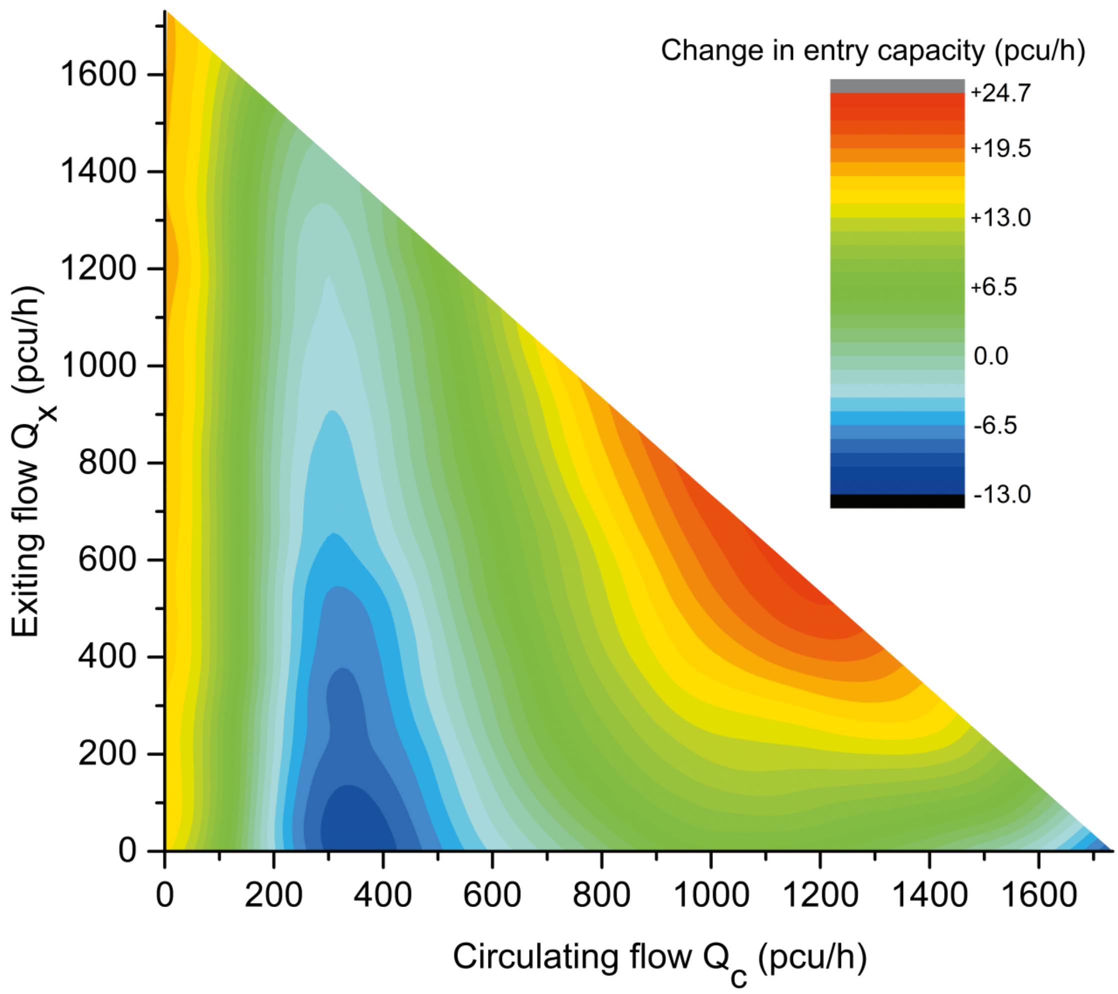
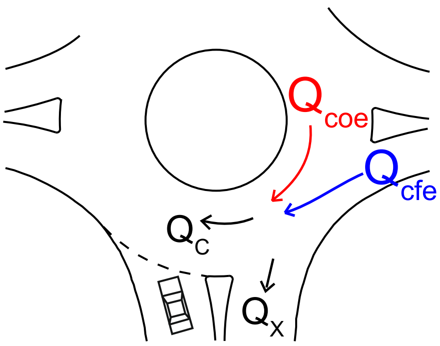


Figure 6-8 Surface plots of relative changes in mean Q_e (from 50 one-hour runs) from middle lane of simplified ThornycroftN model with light vehicles only at the entry, with smoothed contours.

The above was based on a single-lane circulation; for dual-lane circulation, it could be expected that the effects of exiting flows on headways would be greater at higher circulating flows, although there could be secondary effects from the distribution of the vehicles on the circulating lanes. For example, larger exiting flows could probably result in more vehicles exiting from the inner circulating lane rather than just the outer lane. However, there was insufficient empirical data available here to determine how the distribution of circulating lane use might change with different proportions of exiting and circulating flows. In practice, a greater number of approach lanes would likely be designated for a given turning movement if the corresponding demand flow was high. Similarly, the distribution of exiting flows between the outer and inner circulating lanes could also be delay-dependent, and it was not possible to validate the lane choice model in Vissim for the roundabout. Indeed, the occurrence of anomalous lane-changing was a primary reason for the use of single-lane links rather than dual-lane links for the Vissim models – these suggest that the autonomous lane choice modelling algorithm in Vissim requires further development before it can be used to assess the impacts of dual-lane circulation in hypothetical flows.

6.2.3 Circulating flow origin

Given that the results in section 6.2.2 were based on zero flows from the first entry immediately upstream (i.e. the west entry), an alternative explanation raised by the work of Krogscheepers and Roebuck (2000) was that the entry capacity could correlate with the proportion of circulating flows originating from the first upstream entry (denoted C_{upe} here, and illustrated in Figure 6-9).



$$C_{upe} = \frac{Q_{cfe}}{Q_{cfe} + Q_{coe}}$$

Figure 6-9 Definition of C_{upe}

For a given circulating flow, a high exiting flow suppressed the inflow from the immediate upstream entry (Q_{cfe} in Figure 6-9) and was thus significantly correlated (at the 1% level) with C_{upe}. Although the correlation between Q_x and C_{upe} was low at r>-0.16 for all six modelled lanes, this was probably due to the additional variability of Q_{coe} within C_{upe}; indeed, Q_x shows a slightly stronger correlation with Q_{cfe} (r=-0.19) than with C_{upe} (r=-0.12) for the Thornycroft N model.

Nevertheless, the effect of circulating flow origin was investigated by fitting regression models – based on the piecewise model form explained in section 6.3

– onto the data from each Vissim model (assuming all exiting flows were routed through the middle connector). Even after the effect of exiting flow was accounted for, the residuals showed a positive relationship with C_{upe} (Figure 6-10), suggesting that it could be a useful explanatory variable for improving capacity predictions.

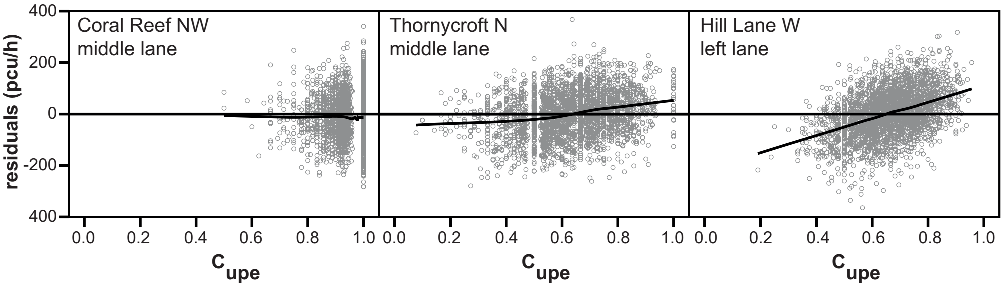


Figure 6-10 Regression model residuals for three entry lanes plotted against the proportion of circulating flow from immediate upstream entry (C_{upe}), with loess lines.

However, the negative correlation between C_{upe} and Q_x suggests that increasing Q_x will actually decrease rather than increase entry capacity, if C_{upe} was not accounted for as a confounding variable. The positive relationship between capacity and C_{upe} is also opposite to that found by Krogscheepers and Roebuck (2000), who used a combination of critical distances and probabilistic gap acceptance in their model instead of the simple time gaps generally used here. The apparent positive effects of exiting flow here could thus be attributed to gap or lag acceptance decisions which differed depending on the origin (and thus acceleration and speed) of the circulating vehicle. However, there was insufficient field data on origin-destination flows to determine the effect of circulation origin in this study; empirical evidence will be needed before including C_{upe} as an additional variable in capacity models.

6.3 Empirical verification

From the various model development issues discussed above including the necessary modifications to the default priority rules for the small roundabout, it is clear that there were inherent simplifications in the constituent gap acceptance models which potentially limit the realism of the Vissim models and any predictive relationships developed directly from them. Validation of the models using independent ground truth capacity data could have helped, but the available dataset was insufficiently large to be subdivided for calibration and validation. Previous work also found no statistically-significant differences between capacity curves from different survey sessions from the same roundabout entry (section 3.5.4), so there would likely have been little benefit from collecting additional validation data from the same roundabouts. Hence, to assess whether the findings from the simulation modelling above could be translated to the real world, the large set of empirical data from Chapter 3 was used to develop a revised capacity model based on relationships suggested by the simulation modelling.

Assuming that there are sufficient roundabout circulatory lanes to avoid capacity constraints, Figure 6-5 suggested a piecewise linear relationship between separation and entry capacity, where decreasing separation below a critical distance threshold (circulating speed × time gap) resulted in a linear reduction in capacity, proportional to the exiting flow (Figure 6-11). The exiting flow in turn had a linear positive effect on capacity at separation distances above the critical distance, but the gradient became negative as the separation reduced.

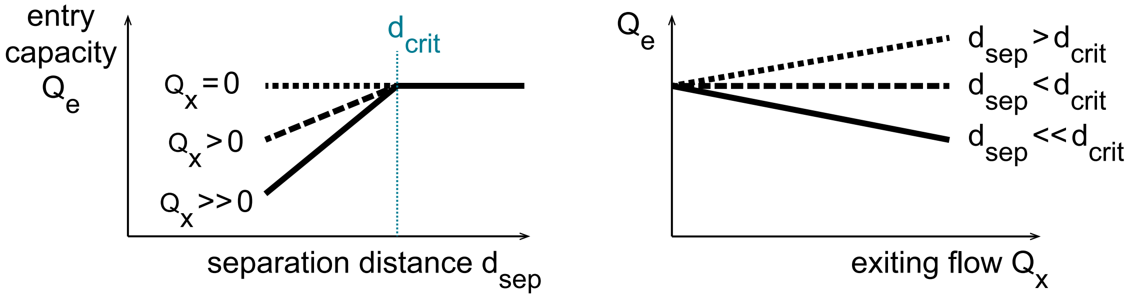


Figure 6-11 Suggested relationships between exiting flows Q_x, separation distance d_{sep} (relative to critical distance d_{crit}) and entry capacity Q_e, assuming other variables unchanged.

Following on from the empirical modelling approach described earlier in section 4.2, there was a need to define critical distance d_{crit} as a function of variables for which data could be relatively easily obtained or was already available in this study. d_{crit} is the product of circulating speed and critical time gap, and its mean is likely to be site-specific rather than constant throughout all sites given differences in circulation speeds.

Limited resources meant that there was no critical gap data or circulation speed data available from the wider database (aside from the circulating speeds for the three simulated roundabout entries). However, it has previously been suggested that the critical gap varies with roundabout size (Brilon, 2014), delays (Polus *et al.*, 2003; Polus *et al.*, 2005), circulating speed (Xu and Tian, 2008), circulating flows (Transportation Research Board, 2007), geometric variables (Troutbeck, 1989; Hagring, 1997a; Hagring, 1997b) and exiting flows (Hagring, 2001). However, despite its known inhibitory effects, exiting flow was usually ignored in gap measurements in most studies, resulting in a lack of good empirical models for critical gap. Most gap acceptance models (e.g. HCM2010 and Brilon-Wu) do not treat critical gaps as site-specific, so here, it was decided here to assume that the critical time gap was a constant value for all entry lanes which could be regressed from the dataset.

The circulating speed, on the other hand, could be related to the geometry. For the three roundabouts analysed in this study, the NCHRP 672 (Transportation Research Board, 2010b, p.6-57) equation relating speed, vehicle path radius and superelevation could be applied. This equation can be expressed as speed V (km/h) = $8.7623\ R_v^{0.3861}$, where R_v is the radius of the vehicle path in metres and superelevation = +0.02 assumed as per design standard (Department for Transport, 2007b). This predicted the mean circulating speed within 10% accuracy, albeit erring on the underestimation side for all three roundabouts (Table 6-1). While there was a systematic trend apparent where the error increased with larger roundabouts, it was not possible to recalibrate the speed model without further measurements of circulation speeds at many more sites.

Table 6-1 Comparison of actual circulating speeds against those predicted by NCHRP 672 equation.

Roundabout	Actual mean circulating speed averaged over circulating lanes (km/h)	Predicted speed based on circulating centreline and 2% superelevation (km/h)	Error (%)
Coral Reef NW	33.4	31.0	-7.2
Thornycroft N	41.3	37.1	-10.2
Hill Lane W	23.0	22.1	-3.9

Using the NCHRP 672 speed equation, and assuming that the mean minimum time gap accepted by drivers was the same for all roundabouts (and therefore the critical distance was directly proportional to the circulating speed), a new nonlinear least-squares regression model for lane entry capacity was developed from the wider empirical database of 1753 flow data points from 35 roundabout entry lanes collected earlier (Chapter 3):

$$Q_e = 1627\ e^{-0.00095Q_c} - 621.3 - 0.049\ Q_x\ [\max[0, (5.058\ (D - 0.5\ W_c)^{0.3861} - d_{sep})]]$$

$$+ 0.051\ Q_x + 4.06\ D + 1661\ (1/r) + 46.3\ W_c$$

where r is the subject entry radius (in m), W_c is the circulatory carriageway width (m), and the other terms as defined previously. The new model had an R^2 of 0.833, adjusted R^2 of 0.832 and RMSE of 123.7 pcu/h, and all its parameters were significant at the 5% level (verified through bootstrap analyses).

The relatively good fit of this new piecewise model, and the significance, direction and size of the model coefficients, suggest that the postulated mechanisms found in the simulation also exist in the field. The equation above thus provides a good description for the relationship between exiting flow, separation distance and entry capacity.

If the NCHRP 672 speed equation and the definition of critical distance gap (constant time gap × speed) assumed for this model were both valid, the regressed coefficient in the piecewise term in the model suggested that the equivalent time gap from the field data was 2.7 seconds. This value is close to the 2.6 seconds assumed for majority of the time gaps used in the Vissim models, and could be even closer (by 0.056 seconds) if the NCHRP 672 speed model was recalibrated as per section 6.4.1 below.

This model assumed that the circulatory carriageway was of sufficient capacity to avoid very high correlations between Q_x and Q_c (there was no evidence of circulating capacity constraints occurring in the field; they would also be likely be prevented during the design stage by adding circulating lanes). If the circulatory carriageway capacity became a constraint, it could be expected that the additional variation explained by the positive impact of Q_x (beyond that of Q_c) would be much less, particularly at large separation distances. One solution would be to replace the coefficients of the Q_x and/or Q_c terms in the model with piecewise functions based on circulation capacity. However, this was beyond the scope of this study as it was not possible to determine the actual capacities of the surveyed circulatory sections.

6.4 Possible sources of remaining error in piecewise model for separation and exiting flow

When comparing the sum of the ranks of the three regression models developed in this study (ranked by lowest RMSE values), the exponential model and the piecewise model equally provide the best fit for all the individual sites in the dataset, as shown in Figure 6-12. These thus suggest that the piecewise and the exponential models were the better models in terms of explaining site-to-site variability. Repeating the validation analyses of section 4.2.6 for the piecewise model suggested that it had slightly lower transferability compared to the exponential model, in which RMSEs which were higher, with 169.0 and 126.0 pcu/h (c.f. 157.6 and 118.4 pcu/h) for Coral Reef NW and Binfield NE respectively, when these sites were separately used for validation rather than calibration. However, for predictive purposes beyond this dataset, the choice between the linear model, exponential model and the piecewise model developed in this study will likely depend on further validation with new data from additional roundabouts.

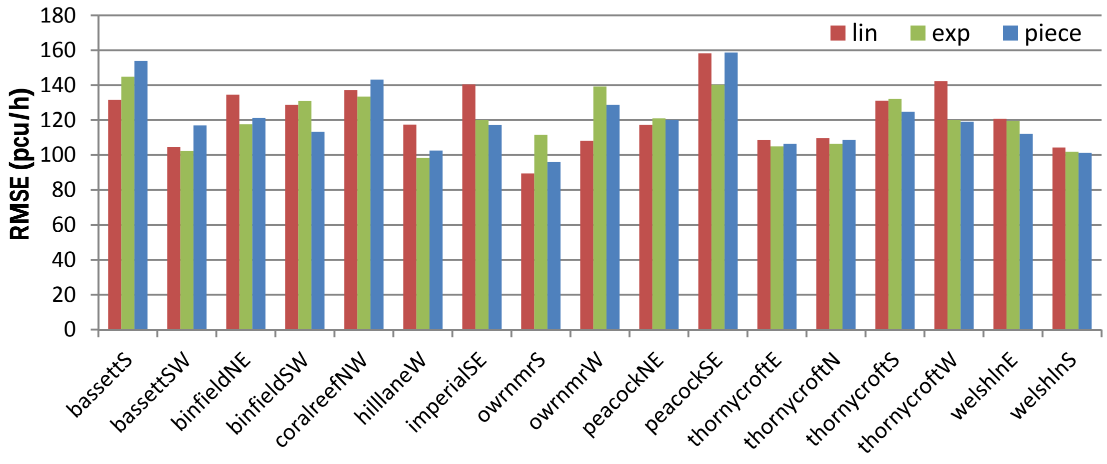


Figure 6-12 Comparison of RMSE values of all sites from the linear, exponential and piecewise regression models.

The piecewise model did not provide a greatly improved fit compared to the exponential model, despite its better-developed model of the impacts of separation and exiting flow compared to the relatively simple linear and two-way interactions assumed in the exponential model. Possible reasons for this are discussed below.

6.4.1 NCHRP 672 speed model

Noting that there was no major improvement in model fit achieved with the piecewise model, it is possible that the NCHRP 672 speed equation may be a source of systematic error. Tentatively, recalibrating the speed equation to the three observed average circulating speed data points available yielded a revised equation of $8.0441R_V^{0.4370}$ as opposed to the original equation of $8.7623R_V^{0.3861}$ as shown in Figure 6-13. However, rerunning the nonlinear regression for the piecewise model yielded identical R^2 values as before, suggesting that the recalibrated NCHRP 672 speed model did not perform better than the original equation for the whole dataset.

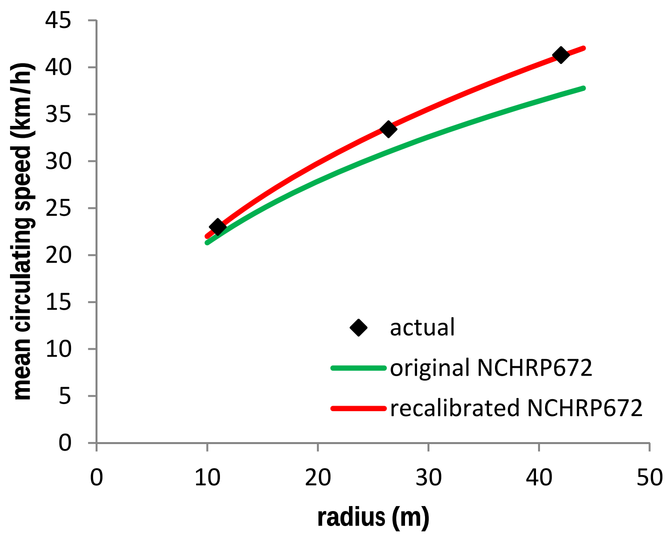


Figure 6-13 Actual mean circulating speeds averaged over the circulating lanes, compared against the original and recalibrated NCHRP 672 speed models based on circulating carriageway centrelines.

6.4.2 Other exiting flow effects omitted from microscopic simulation modelling

Another possible source of model specification error was effects which were not included in the microscopic simulation modelling and therefore excluded from the piecewise regression model. For example, in the case of a large exiting flow combined with few circulating vehicles (originating from entries before the first one upstream), drivers may begin to expect that vehicles coming around the island are more likely to be exiting rather than circulating. At small roundabouts, vehicles inside the critical distance and upstream of the separation point would normally inhibit drivers at the entry as they are conservatively expected to circulate/conflict rather than exit (Figure 6-14, left). However, if they are assumed by default to be exiting rather than circulating, drivers at the entry may begin to ignore them (Figure 6-14, right), unless they begin circulating past the separation point.

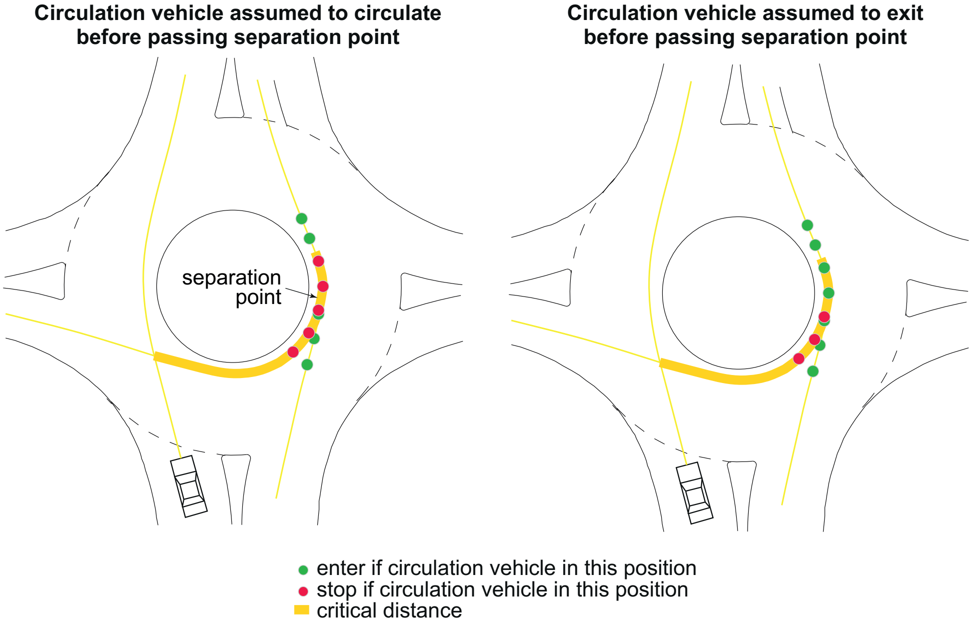


Figure 6-14 Comparison of stop-go behaviour of vehicle at entry depending on the anticipated direction of the vehicle on the circulation.

In this case, given that the circulating vehicle would have already encroached into the critical distance, it would be forced to slow down to avoid colliding with entering vehicle which has already begun crossing the give-way line. The entering vehicle would also accelerate harder than usual for the same reason. These ‘inadvertent’ priority-forcing events contrast with those arising from deliberately-aggressive entering drivers who expect circulating vehicles to slow down for them. It would be difficult to distinguish between the two types of forced-entry events from roadside observations, although inadvertent priority-forcing would be more likely to occur at low circulating flows whereas aggressive priority-forcing would likely be more frequent at very high circulating flows.

This phenomenon – ‘instigative’ in the sense that a large exiting flow encourages more inadvertent priority-forcing – was occasionally observed at BassettSW, which was a roundabout that was effectively operating as a three-armed roundabout with two dominant turning movements per entry. A few vehicles from the north arm performed U-turns rather than exit towards the southwest, but they were visibly forced to decelerate as vehicles entered from the southwest, not expecting the U-turn movements. This phenomenon could also be occurring to some extent at other roundabouts with heavy exiting flows, such as Coral Reef NW, but it was not possible to quantify the effect empirically. If it was significant, it would result in a higher capacity than expected for a given set of circulating and exiting flows.

More importantly, if entering drivers assumed all vehicles coming around the island were intending to exit rather than circulate, this could also result in a negative (rather than only positive or nil) relationship between separation distance and capacity. Referring to the right of Figure 6-14, entering drivers are prompted to reject gaps or lags only when circulating vehicles pass the separation point, rather than when they begin encroaching into the critical distance (i.e. critical distances are no longer explicitly considered for gap acceptance). The further upstream the separation point is, the earlier the lag/gap is rejected i.e. the rejected lags/gaps become larger as the separation distance increases, reducing entry capacity for a given circulating headway. This phenomenon could result in large acceptable gaps being inadvertently rejected, and thus partially explain the existence of inconsistent driver behaviour where a driver's accepted gap is smaller than his/her maximum rejected gap – these had been previously been attributed to inattentiveness (Troutbeck and Brilon, 2001; Troutbeck, 1992), and possibly waiting time (Polus *et al.*, 2003).

A negative relationship between separation distance and capacity was partly reflected in the linear and exponential empirical models, as shown in Figure 4-9. For example, in the linear model, there appeared to be a decrease in capacity with increased separation at low circulating flows, particularly for the larger roundabouts. For the exponential model, increased separation resulted in lower capacity for large roundabouts, but not for small roundabouts where inhibitory effects would have dominated. The ARCADY large roundabout model (Semmens, 1988) also had a negative relationship between separation distance and capacity. However, the piecewise model does not have a negative relationship between separation distance and capacity, as it did not consider the instigative effect. Hence, it is possible that the instigative effect above resulted in the piecewise model having a marginally poorer model fit compared to the exponential model.

In principle, this instigative phenomenon could be modelled in microscopic simulation by modifying the priority rules to take into account the relative flows at the roundabout. However, it will not be possible to develop, calibrate or validate suitable vehicle interaction rules without empirical data. Such data will likely have to be obtained from drivers' perspectives rather than from the roadside, and resource limitations meant that such investigations were beyond the scope of this study.

6.4.3 Other factors and variables

Aside from functional form, model specification errors which limit the ability of the models to account for site-to-site variability also originate from the choice of included inputs. However, given that the capacity lines produced by comparatively flexible all-variable neural network (Figure 4-7) also differ quite considerably from actual data despite some over-fitting (section 4.2.6), it is likely that a large part of the unexplained site-to-site variability also originates from factors and variables not included in this study.

These excluded factors and variables could include driver behaviour arising from intrinsic factors (e.g. physiology, attitudes, etc. – rather than from aspects of roundabout design such as sight distances or geometry) or vehicle characteristics (e.g. accelerative ability) on the aggregate user-population level. Local mean critical gaps and follow-on headways could, in principle, be used to quantify such differences in driver/vehicle populations. Indeed, as NCHRP 572 (Transportation Research Board, 2007) concluded that differences in driver behaviour was the main reason for capacity differences between sites, site-specific calibration of the HCM2010 model is based on measured critical gaps and follow-on headways (Transportation Research Board, 2010a). However, there remains a limited understanding of the effect of design-related factors on critical gaps and follow-on headways, so it is difficult to segregate the components of variability arising from driver population characteristics from those influenced by geometric design or traffic flows; this would be necessary to quantify any population-specific differences.

Even if behavioural differences in driver or vehicle populations could be quantified for macroscopic capacity models, this may not be necessary apart from highly exceptional cases such as say, a roundabout entry used almost exclusively by elderly drivers. This is because there is yet to be any statistically significant evidence for regional differences in critical gaps, given the often considerable variations in estimated critical gaps within a region or even within a single roundabout (Wei and Grenard, 2012; Xu and Tian, 2008). Wider-scale international comparisons (e.g. Vasconcelos *et al.*, 2013, Table 3; Transportation

Research Board, 2007, Table 37) initially suggest possible differences in average critical gaps, but these could be also be due to differences in critical gap estimation methods as well.

It is thus likely that a large part of the between-site residual errors arises from some other aspects of the roundabout design unrelated to driver or vehicle population, which were excluded from this study. An example was the circulating flow origin discussed in section 6.2.3, but Kimber (1989) also suggested that other factors such as road surface conditions, detailed road alignments and sightlines. However, given the relatively complex and bespoke geometries of roundabout carriageways, approach roads and vehicle trajectories, it has not been feasible thus far to quantify some of these aspects for analysis in this research. Also, as illustrated by the questions over circulating flow origin, variables could be also have been omitted simply due to practical constraints on empirical data collection.

6.4.4 Implications

Given the above, just as with existing state-of-the-art models, a calibration parameter may be necessary to fit the chosen final model on new sites, where warranted by empirical evidence from existing similar sites. Such a calibration parameter must be practicably measurable from field data, and there should also be a clear understanding of how it relates to other input variables. Identifying a suitable calibration method will thus require future research, as does assessing the extent to which the uncalibrated final regression models above is inherently transferable to other geographic contexts.

6.5 Chapter conclusions

Given the findings from the empirical modelling in Chapter 1 regarding the significant impacts of separation distance and exiting flow on entry capacity, calibrated microscopic simulation models of three roundabout entries were developed for experimental investigations into the nature of these impacts. Using a novel approach to replicate the effect of varying separation distances, the simulation work demonstrated that exiting vehicles had a clear negative and inhibitory effect on entry capacity when the separation distance was below a critical distance threshold. This threshold was a product of the minimum acceptable time gap and circulating speed, and was specific to the roundabout and the different lanes of the same entry.

Beyond the critical distance threshold, exiting flows did not have a negative impact on gap acceptance, and an inherently near-linear positive relationship with capacity became evident as inhibitory effects no longer dominated. This positive effect appears to be due to exiting vehicles leaving distinct gaps behind in the headways of the remaining circulating stream, with the resulting changes in headway distributions enabling increased capacity. It may also be related to the proportions of the circulating stream originating from the immediate upstream entry and possibly differences in the gap acceptance behaviour depending on the origin of the circulating vehicles. However, there was not enough field data to verify the sensitivity of capacities to the origin of circulating flows, for which additional empirical research is required.

The mechanisms suggested by the microscopic simulation modelling work were translated into a functional model relating exiting flow, separation distance and entry capacity, which was then used as the basis for regression using field data from a wide range of roundabouts. The good fit of the model suggests that the piecewise relationship developed appears to provide a good description for the effects of exiting flow and separation on entry capacity, and provided empirical verification of the hypothesised relationships between these variables. By providing a better understanding of the impact of separation and exiting flows on lane entry capacity, the findings could be used to improve on the prediction of lane capacity and henceforth enable the better design and planning of roundabouts.

Chapter 7: Discussion and Conclusions

7.1 Summary and discussion

To address the aim in this research of improving our ability to model roundabout capacity accurately and therefore achieve better roundabout design, there have been three major phases to the research presented in this thesis. The first phase, comprising an extensive literature review, has shown that despite extensive research since the genesis of modern offside priority roundabouts, there remains a substantial gap in existing knowledge in terms of the factors and variables which affect capacity. This gap is reflected in the inconsistencies in significant inputs among existing state-of-the-art roundabout capacity models as well as major differences in the models' methodological foundations.

Using empirical data collected from the field, the second phase of the work has demonstrated that this gap in knowledge results in limitations on the accuracy of existing roundabout capacity models. Two new empirical models for lane capacity based on exponential-in-Q_c and linear-in-Q_c forms were developed and benchmarked against neural networks. It was shown that these models were better at explaining the variation in capacities than existing models, which illustrate the potential gains in accuracy if the appropriate explanatory variables were to be included in the model. This phase also identified the importance of two variables (separation distance and exiting flows), which have not previously been included in the majority of existing capacity models such as ARCADY, SIDRA and HCM 2010. The empirical models also raised questions over how these two variables affected entry capacity, given that the effects shown by this and other empirical work appeared to contrast with those found in previous research based on analytical and simulation approaches.

The third major phase of this study thus investigated the impacts of these two particular variables using microscopic simulation. Through three case studies, it was found that the relationship between separation distance and capacity could be expressed through a piecewise linear relationship, and that the effect of exiting flow changed from positive to negative as the inhibitory effects increased. This relationship was incorporated into the previous exponential-in-Q_c model; the resulting new model produced similar predictive performance but provided a better explanation for the effects of separation distance and exiting flow.

In terms of engineering application, one caveat to the use of macroscopic capacity models such as the ones developed in this thesis is the additional need to separately model the relationship between capacity and delays. This is because journey-time savings are often an important measure of effectiveness in transport scheme appraisal, apart from RFC (Department for Transport, 2012). Although capacity-delay models exist – e.g. Kimber and Hollis (1979) or Akçelik and Troutbeck (1991, cited in Akçelik *et al.*, 1998) – empirical evidence for the validity of these has been relatively limited (Kimber and Daly, 1986). Whilst microscopic simulation approaches are theoretically advantageous in this respect, Chapter 1 has illustrated that they can require considerable calibration (and data collection) effort if they are to model entry behaviour accurately. Indeed, the same argument applies to the use of theoretical gap acceptance models, as there remains relatively little understanding of the factors affecting critical gap, follow-on headways and circulating headway distribution parameters.

The limitations on resources necessarily restricted the scope of the study to quantifying the effects of separation distance and exiting flows on lane capacities. However, the empirical models showed that there are clearly more variables which significantly affect capacity, which are also worth further investigation. Linearity by default was assumed for their effects but – as demonstrated by the piecewise relationship developed for separation distance and exiting flows – there could be other nonlinear forms which could better explain their impacts on capacity. There could also be significant correlations and interactions between several of the explanatory variables, which could also manifest in apparent nonlinear relationships.

The limitations of empirical and microscopic simulation modelling methods have been discussed in sections 2.2.3 and 2.2.5.2; and these caveats apply to the applications of those methods in this study. The empirical models here have been developed using sufficient data collected within this study, but for wider application to the design of roundabouts, there necessarily needs to be more data needed to validate their applicability to say, other geographic regions.

It is noted that this study was limited to examining lane entry capacities, which are typically achieved in unflared entries or lanes. However, many roundabouts in the UK have flared entries, and the flaring effects discussed in section 2.1.2 can considerably limit the lane entry flows, particularly with the occurrence of lane starvation. As a result, the lane capacity models in this study should be integrated with a separate model for flaring, such as Entry Lane Simulation of ARCADY 8 (Burtenshaw, 2012) or analytical models (Wu, 2006; Wu, 1999; Akçelik, 1997). In addition, link capacity can also constrain the achievable capacity of the roundabout, particularly in over-saturated conditions where stop-and-go waves begin to appear in the queues.

Notwithstanding these caveats, the research presented in this thesis has addressed the research objectives in section 1.3 which were aimed at improving on our current knowledge and understanding of roundabout capacity modelling for more accurate capacity predictions and hence better roundabout design. In particular, given the relatively limited resources available, this research has focussed on developing a better understanding of two significant variables which improve the prediction of roundabout entry capacity, and demonstrated how their inclusion could result in improved capacity models.

7.2 Key conclusions

- There has been extensive research and development into the capacity of modern offside priority roundabouts since the 1970's.
- Despite this, there remains a major gap in existing knowledge with regards to the factors and variables which affect roundabout entry capacity.
- This is reflected in the differences and inconsistencies in inputs and methodologies between existing state-of-the-art models.
- Evaluations with recent data collected from 35 roundabout entry lanes in the field have shown that this limits the accuracy of state-of-the-art models, particularly in their ability to explain site-to-site variation in entry capacities.
- New empirical models have thus been developed for lane capacity using regression, and benchmarking against neural networks showed that they performed well with the shortlisted explanatory variables.
- These regression models were based on exponential-in-Q_c and linear-in-Q_c forms, and outperformed existing state-of-the-art models.
- In the new models, separation distance and exiting flows were found to be more useful predictor variables (when used in conjunction with other

variables) compared to others used in more-established models (e.g. entry radius and entry angle).

- To investigate the effects of separation distance and exiting flows through microscopic simulation, stochasticity in separation distances was modelled through a novel approach in Vissim involving multiple exit connectors. This was significant as the variability of separation distances had not been explored before, whether through analytical or simulation approaches.
- The separation distance was found to have a piecewise linear relationship with capacity, while exiting flows have a linear positive relationship which becomes negative as the inhibitory effect increases at low separation distances.
- The two main mechanisms explaining these effects of exiting flows were the inhibitory mechanism, and changes in circulating headways.
- A revised empirical model incorporating this piecewise relationship performed as well as the exponential-in-Q_c and linear-in-Q_c models, suggesting that the impacts of exiting flows were modelled reasonably well.
- By improving our understanding of the impacts of these two variables on capacity, this is an important step towards the improved modelling of roundabout entry capacity.

The above findings in this thesis represent original contributions to knowledge, as evidenced by published outputs comprising the following journal papers and conference papers:

- YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (under review) The Impact of Exiting Flows on Roundabout Lane Entry Capacity, Transportation Planning and Technology, UTSG 2015 Special Issue, Routledge.
- YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (in press) Models of Roundabout Lane Capacity, Journal of Transportation Engineering, American Society of Civil Engineers. doi: 10.1061/(ASCE)TE.1943-5436.0000773
- YAP, Y. H., GIBSON, H. M. & WATERSON, B. J. (2013) An International Review of Roundabout Capacity Modelling, Transport Reviews, 33 (5), pp. 593-616. doi: 10.1080/01441647.2013.830160
- YAP, Y. H. (2015) The Impact of Exiting Flows on Roundabout Lane Entry Capacity, 47th Annual Conference of the Universities' Transport Study Group, London, 5-7th January 2015. (Smeed Prize runner-up)

- YAP, Y.H., GIBSON, H. & WATERSON, B. (2014) Improved Models of Roundabout Lane Capacity. 46th Annual Conference of the Universities' Transport Study Group, Newcastle upon Tyne, 6-8th January 2014.

7.3 Suggestions for future research

This research is clearly an important step towards developing a more complete model of roundabout entry capacity. With further development, the empirical models and the findings from this research could form the foundations of new entry capacity models for engineering application, particularly when integrated with suitable models for multilane flare effects, lane choice, as well as queue and delays.

Before the models can be used in general practice however, further research into the following areas is recommended:

- Extending and validating the empirical models through a geographically-wider database and more capacity flow measurements. This is particularly important to assess the ability of the models to replace existing models (e.g. the LR942 model in ARCADY) for estimating lane capacity.
- Verifying the macroscopic functional forms for the other hypothesised explanatory variables in this study. Having a better model of, say, the effects of diameter on capacity, could provide useful improvements in the accuracy of the models in this study, and improve their transferability. This will necessarily involve increased empirical data collection (possibly with larger saturated time intervals for reduced variability in capacity flow data points), or human factors research based on naturalistic driving or improved driving simulators.

To further extend the capabilities of the models, the following topics also require additional research:

- Evaluating the applicability of the new lane capacity models to mini-roundabouts, very large roundabouts and compact roundabouts.
- Developing improved data collection systems for vehicle kinematic and interaction behaviour at roundabouts, which may include recording positions, distances, speeds and accelerations through video image recognition, wireless sensors (e.g. Bluetooth), embedded detectors or other methods. These could

then be used to efficiently quantify flows, headways, queue lengths, delays, origin-destination patterns and other more detailed aspects of traffic behaviour, allowing them to be investigated as explanatory variables for entry capacity. The resulting additional empirical data would also enable a step change in the future development of capacity modelling.

- Developing better gap acceptance, lane-changing and lane-choice algorithms, and validating car-following models for improved microscopic simulation of roundabouts. Given inherent limitations in the diversity of existing roundabout geometry and therefore the amount of empirical data which could be collected, microscopic simulation will likely still play an important role as an alternative to track experiments or gap acceptance theory for the further investigation of other explanatory factors and variables for inclusion in macroscopic models.

Depending on the current state of the art in their respective areas, other pertinent topics to complement the development of roundabout lane capacity models and improve their applicability are:

- Modelling the effects of flaring on entry capacity, including the impacts of lane choice and vehicle queue move-up kinematics. Models of flare effects would then allow the lane capacity models in this study to be applied to flared entries, which are commonly used in several countries such as the U.K. and Australia.
- Modelling the effects of upstream and downstream link capacity on roundabout entry capacity. In urban areas or severely congested highway links, spilling back of queues on the exit links can have a major impact on entry capacity, and could become a more significant problem with long term traffic growth.
- Verifying existing theoretical models of the relationships between entry capacity, queues and delays for macroscopic models using empirical data.

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Appendices

Appendix A

Aerial photographs of sampled roundabouts from Google Earth (Google Inc., 2013) and its various suppliers. Survey periods AM and PM correspond to morning (~7.30 am start) and afternoon peak traffic respectively (~4.15 pm start).

A.1 coralreef roundabout

Arm surveyed:

- North West

Surveyed peak periods:

- 03 May 2012 AM
- 27 June 2012 AM

A.2 imperial roundabout

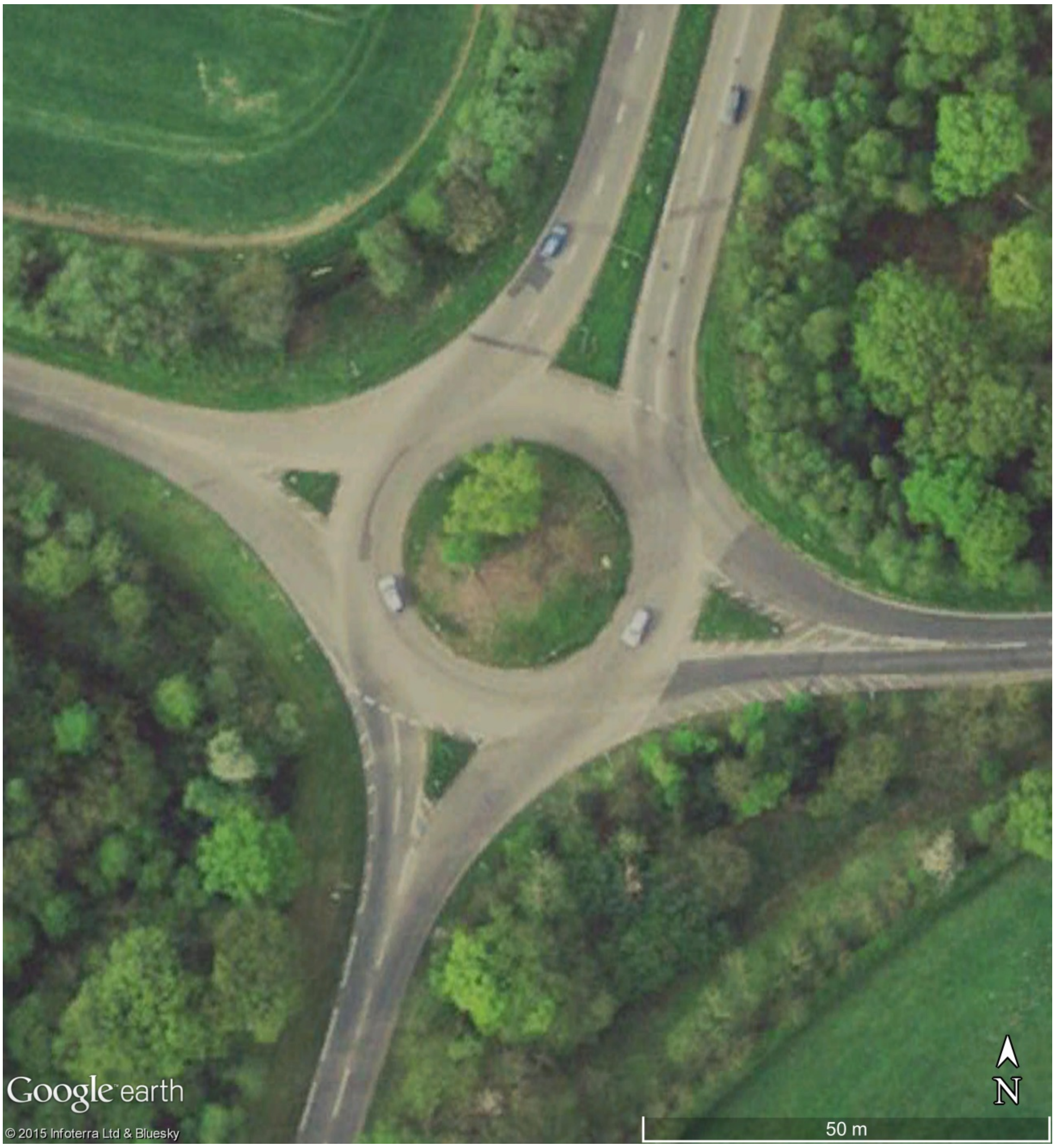
Arm surveyed:

- South East

Surveyed peak periods:

- 19 July 2012 PM

A.3 welshln roundabout



Arm surveyed:

- South
- East

Surveyed peak periods:

- 16 July 2012 AM

A.4 baswinc roundabout

Arm surveyed:

- South West
- South East

Surveyed peak periods:

- 03 July 2012 AM

A.5 binfield roundabout

Arm surveyed:

- North East
- South West

Surveyed peak periods:

- 13 July 2012 AM
- 16 July 2012 AM

A.6 peacock roundabout

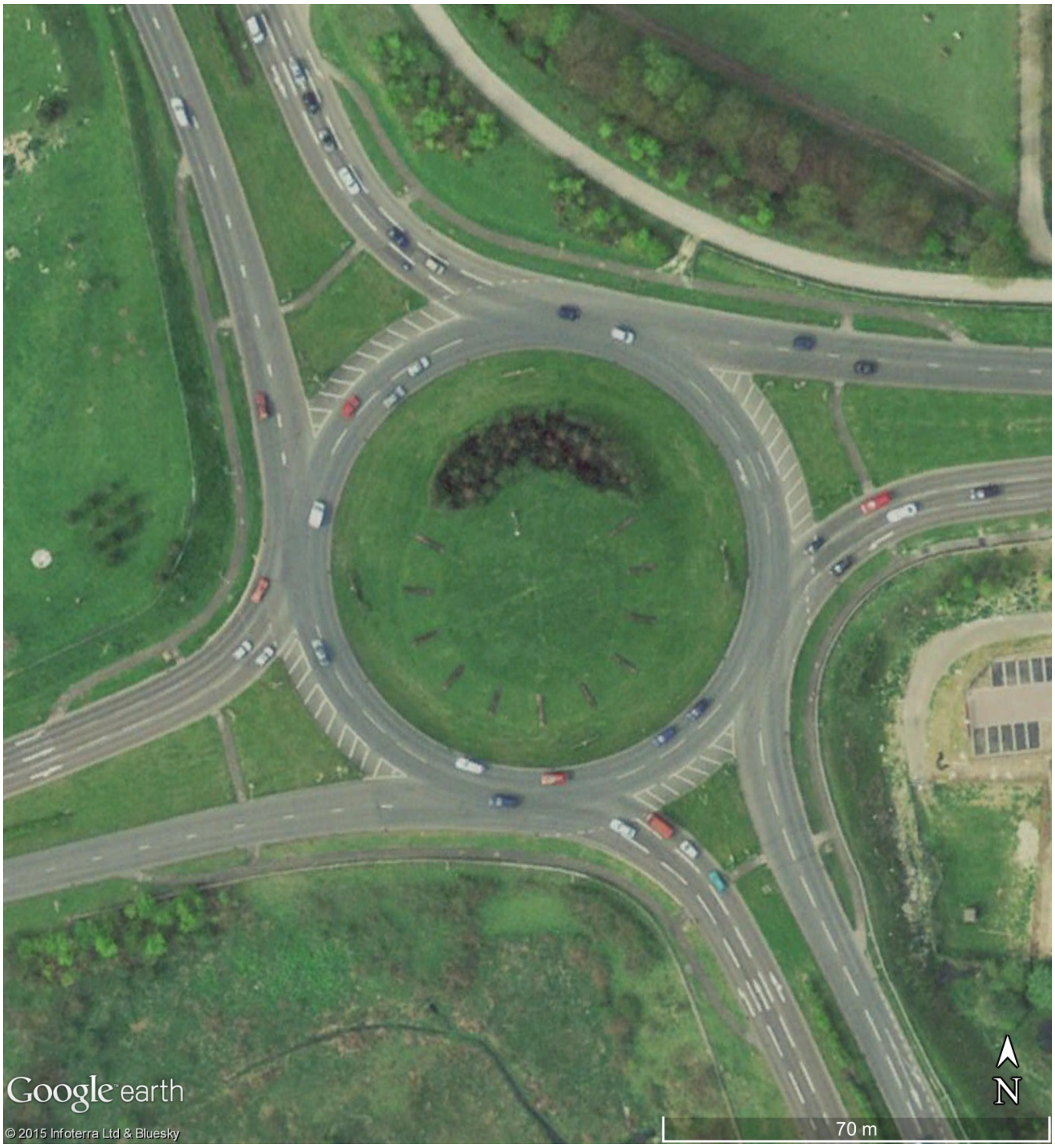
Arm surveyed:

- North East
- South East

Surveyed peak periods:

- 01 June 2012 PM
- 02 July 2012 PM

A.7 thornycroft roundabout



Arm surveyed:

- North
- East
- South
- West

Surveyed peak periods:

- 18 May 2012 AM
- 13 February 2013 AM
- 14 February 2013 PM
- 15 February 2013 AM
- 15 February 2013 PM

A.8 owrnmr roundabout

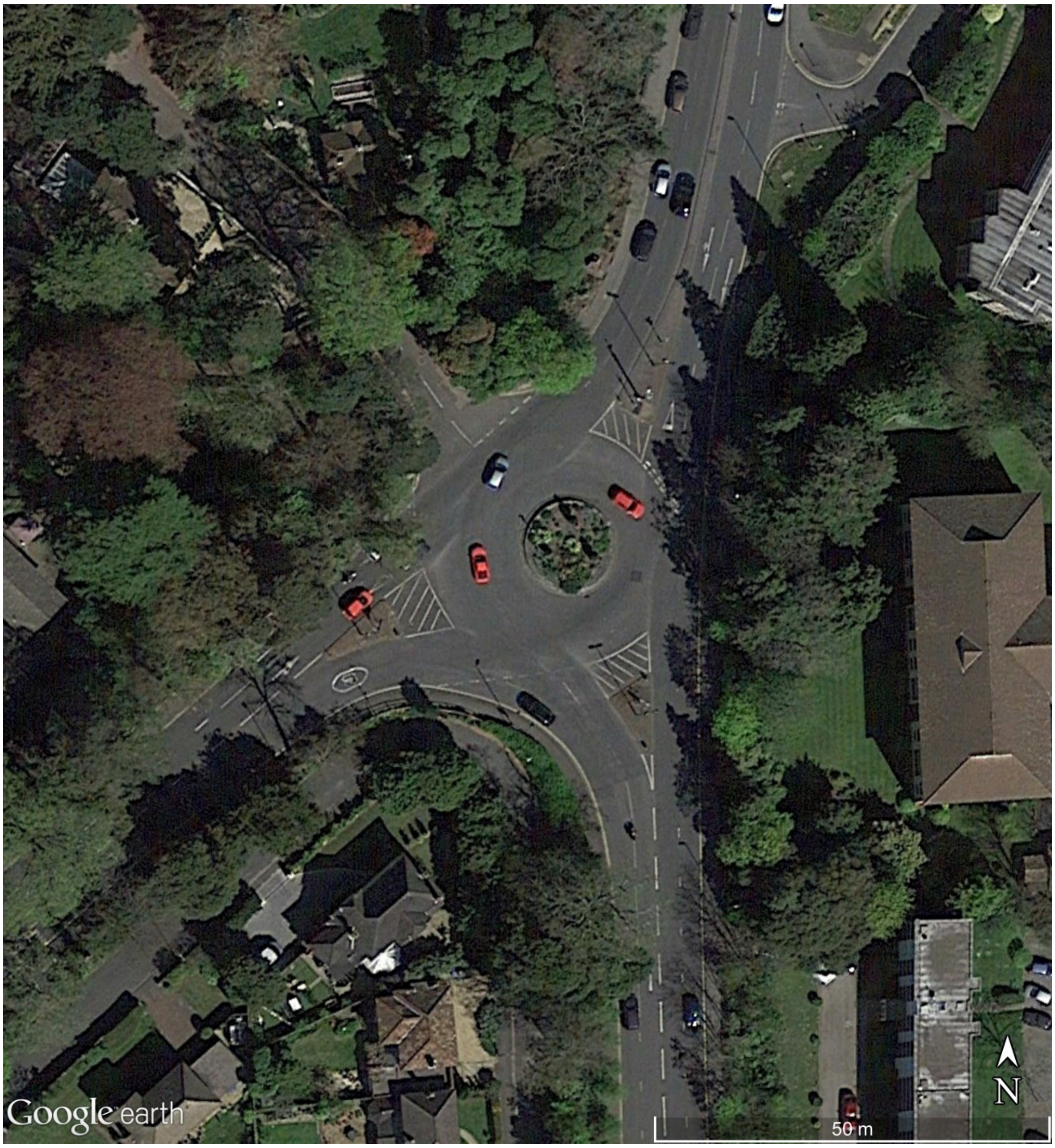
Arm surveyed:

- South
- West

Surveyed peak periods:

- 18 October 2012 AM
- 04 July 2012 PM
- 18 July 2012 PM

A.9 bassett roundabout



Arm surveyed:

- South
- South West

Surveyed peak periods:

- 02 August 2012 AM
- 28 January 2013 AM
- 30 January 2013 PM
- 31 January 2013 PM
- 01 February 2013 PM

A.10 hilllane roundabout

Arm surveyed:

- West

Surveyed peak periods:

- 04 February 2013 AM
- 04 February 2013 PM
- 07 February 2013 AM
- 07 February 2013 PM

Appendix B

B.1 Entry lane data

Index no.	site	lane	Data pts.	mean Q_e (pcu/h)	mean Q_c (pcu/h)	mean Q_x (pcu/h)	v (m)	e (m)	l' (m)	r (m)	D (m)	ϕ (°)	d_{sep} (m)	d_{upe} (m)	W_L (m)	W_C (m)	L.L.S.$^+$ slope	L.L.S.$^+$ intercept
1	bassettS	M	61	481.0	1077.0	1059.3	2.6	3.7	2.2	20	35	20*	22.4	29.8	2.9	8.2	-0.912	1463
2	bassettS	R	64	524.1	1076.3	1081.9	2.7	3.5	6.7	221	35	29*	18.2	25.6	3.0	8.2	-0.783	1366
3	bassettSW	L	32	643.1	1368.8	783.8	3.1	3.2	0.8	∞	33	32*	15.5	71.5	3.0	11.6	-0.313	1071
4	bassettSW	R	26	570.0	1363.8	763.8	3.2	3.7	2.8	∞	33	34*	11.8	63.2	2.9	11.6	-0.339	1033
5	baswincSE	L	52	435.0	1482.7	-	3.8	3.9	3.2	50	95	16	99.6	121.4	3.0	8.0	-0.264	826
6	baswincSE	R	28	420.0	1491.4	-	3.4	4.0	3.5	76	95	36	91.8	113.6	3.5	8.0	-0.112	588
7	baswincSW	L	61	877.4	924.6	-	3.1#	3.1	0	66	93	7*	51.1	71.5	3.3	8.0	-0.408	1255
8	baswincSW	R	50	805.2	955.2	-	3.1#	3.1	0	66	93	26	42.8	63.2	3.2	8.0	-0.410	1197
9	binfieldNE	L	75	736.8	1103.2	984.0	3.6#	3.6	0	26	81	12*	50.1	63.4	3.4	6.7	-0.596	1394
10	binfieldNE	R	59	755.6	1098.3	971.2	3.6	3.6	10.2	30	81	18*	43.4	56.7	3.6	6.7	-0.657	1477
11	binfieldSW	L	20	453.0	1629.0	816.0	3.0	3.3	8.1	65	81	9*	49.2	58.0	3.1	6.7	-0.441	1171
12	binfieldSW	R	9	300.0	1760.0	706.7	2.6	3.4	5.8	41	81	10*	35.8	44.6	2.7	6.7	-0.719	1565
13	coralreefNW	M	68	926.5	943.2	1697.6	3.1#	3.1	0	81	62	29	36.6	48.7	3.2	9.1	-0.542	1438
14	coralreefNW	R	55	946.9	948.0	1761.8	3.5#	3.5	0	82	62	30	30.4	42.5	3.0	9.1	-0.567	1485
15	hilllaneW	L	67	438.8	1209.9	394.0	3.3	4.1	4.6	100	31	16*	25.7	31.9	3.5	9.1	-0.462	998
16	hilllaneW	R	50	352.8	1252.8	387.6	3.7	4.6	7.9	487	31	50	12.8	19.1	4.0	9.1	-0.434	896
17	imperialSE	M	46	1393.0	340.4	1425.7	3.7	5.2	9.3	172	60	35	29.5	49.8	4.2	10.6	-1.055	1752
18	imperialSE	R	48	1425.0	326.3	1377.5	3.9#	3.9	0	173	60	54	23.9	44.2	3.7	10.6	-1.011	1755

Index no.	site	lane	Data pts.	mean Q_e (pcu/h)	mean Q_c (pcu/h)	mean Q_x (pcu/h)	v (m)	e (m)	l’ (m)	r (m)	D (m)	ϕ (°)	d_{sep} (m)	d_{upe} (m)	W_L (m)	W_C (m)	L.L.S.[+] slope	L.L.S.[+] intercept
19	owrnmrS	L	12	730.0	860.0	260.0	3.0[#]	3.0	0	20	36	17*	20.3	29.6	2.3	7.0	-0.474	1138
20	owrnmrW	L	48	620.0	1158.8	503.8	3.5	3.5	0	20	36	26	21.5	31.0	3.1	7.0	-0.597	1311
21	peacockNE	M	84	669.3	1112.1	319.3	3.0	3.9	53.1	48	79	44	42.7	91.9	3.3	8.0	-0.451	1171
22	peacockNE	R	84	750.7	1112.1	319.3	3.6	4.2	3.1	55	79	54	37.0	86.1	3.1	8.0	-0.582	1398
23	peacockSE	L	57	577.9	1896.8	669.5	3.3	3.9	21.2	28	79	16	45.7	62.6	3.5	8.2	-0.300	1146
24	peacockSE	M	42	532.9	1951.4	665.7	3.2	4.1	7.2	30	79	39	37.3	54.2	3.3	8.2	-0.329	1175
25	thornycroftE	M	82	444.1	1964.6	676.1	2.4	3.1	13.5	70	92	41	66.8	89.4	3.3	8.2	-0.228	891
26	thornycroftE	R	88	465.7	1941.8	663.4	3.4	3.8	3.0	45	92	48	61.6	84.2	3.2	8.2	-0.298	1044
27	thornycroftN	M	39	686.2	1350.8	1806.7	2.9	4.1	11.3	56	92	9	63.8	80.2	3.2	8.2	-0.454	1299
28	thornycroftN	R	39	712.3	1350.8	1806.7	3.1[#]	3.1	0	61	92	35*	54.2	70.6	3.5	8.2	-0.509	1399
29	thornycroftS	M	38	680.5	1179.5	1318.4	3.8[#]	3.8	0	91	92	16*	46.2	63.2	3.3	8.2	-0.530	1305
30	thornycroftS	R	31	667.7	1238.7	1298.7	3.3[#]	3.3	0	62	92	17*	39.7	56.7	3.4	8.2	-0.502	1289
31	thornycroftW	L	39	549.2	1815.4	703.1	3.6[#]	3.6	0	33	100[@]	15*	67.7	92.7	3.3	8.2	-0.413	1298
32	thornycroftW	M	45	449.3	1846.7	664.1	3.3[#]	3.3	0	34	92	19*	62.2	87.2	3.2	8.2	-0.341	1079
33	thornycroftW	R	22	458.2	1947.3	614.3	3.6[#]	3.6	0	38	92	22*	59.3	84.3	3.3	8.2	-0.363	1165
34	welshlnE	-	85	553.4	1214.1	477.2	3.2	4.3	4.8	88	51	15	38.8	42.5	3.1	9.3	-0.469	1123
35	welshlnS	L	47	972.8	660.0	1155.3	3.2	3.5	8.7	33	51	16*	31.3	44.3	2.6	9.3	-0.814	1510

[+] Linear least-squares

* Entry angle according to the Junctions 8 User Guide Figure 23-4 (Burtenshaw, 2012). All others measured according to Figure 23-3 in ibid.

[#] Approach half-width assumed equal to entry width due to negative flaring (where approach lane width was greater than entry width due to the increased number of narrower lanes at the give-way line)

[@] Left lane geometry almost bypasses circulatory carriageway